

2

# NAVAL POSTGRADUATE SCHOOL

## Monterey, California

AD-A276 738



### THESIS

DTIC  
ELECTE  
MAR 14 1994  
S B D

DEVELOPMENT OF A FREQUENCY-DOMAIN  
ELECTROMAGNETIC SCATTERING  
MEASUREMENT SYSTEM

by

Kenneth K. Oh

December 1993

Thesis Advisor:

Michael A. Morgan

Approved for public release; distribution is unlimited

94-08199



94 3 11 167

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.</small>				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE December 1993		3. REPORT TYPE AND DATES COVERED Master's Thesis
4. TITLE AND SUBTITLE DEVELOPMENT OF A FREQUENCY-DOMAIN ELECTROMAGNETIC SCATTERING MEASUREMENT SYSTEM			5. FUNDING NUMBERS	
6. AUTHOR(S)  OH, Kenneth K.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the US Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT  Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) This thesis describes the development of a system for measuring frequency-domain scattered fields in the Transient Electromagnetic Scattering Range at the Naval Postgraduate School. The new system employs a stepped-frequency CW waveform and utilizes an HP-8510B network analyzer as an RF front-end and a coherent receiver. A pair of AEL H1498 antennas was installed to cover a frequency range of 2 GHz to 18 GHz. An HP-82300C BASIC Language Processor was installed on a COMPAQ Deskpro-386 PC, and an HP-BASIC program was developed for remote control of the HP-8510B with data acquisition over the HPIB bus. A post-processing algorithm was created using MatLab for background subtraction, calibration, and deconvolution. A set of RCS measurements was made using various size spheres, and the post-processing outputs were compared to computed values. Good agreement between these measurements and computed data indicates excellent accuracy of the measurement system and valid operations of the post-processing algorithm.				
14. SUBJECT TERMS  Scattering, radar cross section, anechoic chamber			15. NUMBER OF PAGES 74	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

Approved for public release; distribution is unlimited

Development of a Frequency-Domain  
Electromagnetic Scattering  
Measurement System

by

Kenneth K. Oh  
Electronics Engineer, Department of Navy  
B.S., University of California at Berkeley, 1986

Submitted in partial fulfillment of the  
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL  
December 1993

Author:

*Ken K. Oh*

Kenneth K. Oh

Approved By:

*Michael A. Morgan*

Michael A. Morgan, Thesis Advisor

*David C. Jenn*

David C. Jenn, Second Reader

*Michael A. Morgan*

Michael A. Morgan, Chairman

Department of Electrical and Computer Engineering

## ABSTRACT

This thesis describes the development of a system for measuring frequency-domain scattered fields in the Transient Electromagnetic Scattering Range at the Naval Postgraduate School. The new system employs a stepped-frequency CW waveform and utilizes an HP-8510B network analyzer as an RF front-end and a coherent receiver. A pair of AEL H1498 antennas was installed to cover a frequency range of 2 GHz to 18 GHz. An HP-82300C BASIC Language Processor was installed on a COMPAQ Deskpro-386 PC, and an HP-BASIC program was developed for remote control of the HP-8510B with data acquisition over the HPIB bus. A post-processing algorithm was created using MatLab for background subtraction, calibration, and deconvolution. A set of RCS measurements was made using various size spheres, and the post-processing outputs were compared to computed values. Good agreement between these measurements and computed data indicates excellent accuracy of the measurement system and valid operations of the post-processing algorithm.

Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/Avail	
Availability Codes	
Dist	Avail and/or Special
A-1	

## TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	BACKGROUND.....	1
B.	OBJECTIVE.....	2
II.	SYSTEM DESCRIPTION AND MEASUREMENT SETUP.....	4
A.	OVERVIEW.....	4
B.	SYSTEM DESCRIPTION.....	6
1.	Anechoic Chamber.....	6
2.	HP-8510B Network Analyzer.....	7
3.	Antennas.....	11
III.	REMOTE CONTROL AND DATA ACQUISITION.....	15
A.	REMOTE CONTROLLER HARDWARE.....	15
B.	CONTROL AND DATA ACQUISITION SOFTWARE.....	16
C.	MEASUREMENT PROCEDURES.....	20
IV.	POST-PROCESSING.....	22
A.	ALGORITHM OVERVIEW.....	22
B.	BACKGROUND SUBTRACTION AND CALIBRATION.....	23
C.	DIGITAL SIGNAL PROCESSING.....	26
1.	Window Shape.....	26
2.	Zero Padding and Complex Conjugate.....	30
3.	Fourier Transforms, Gating and Unwindowing..	30
V.	SYSTEM VALIDATION.....	37
A.	CANONICAL TARGETS.....	37
B.	EXPERIMENTAL RESULTS.....	37

VI. CONCLUSIONS.....	47
A. SUMMARY.....	47
B. FUTURE CONSIDERATIONS.....	47
APPENDIX A. SOURCE CODE OF THE "GET_DATA" PROGRAM.....	49
APPENDIX B. SOURCE CODE OF THE "PROC.M" PROGRAM.....	57
LIST OF REFERENCES.....	62
INITIAL DISTRIBUTION LIST.....	63

## LIST OF TABLES

Table 1.	Electrical Characteristics of AEL H1498 Antenna.....	11
Table 2.	Test Matrix of Scattering Measurements.....	38

## LIST OF FIGURES

Figure 1.	Schematic Drawing of the Frequency Domain RCS Measurement System Implemented on the HP-8510B Network Analyzer.....	5
Figure 2.	General Layout of the Anechoic Chamber.....	7
Figure 3.	Interior of the Anechoic Chamber.....	8
Figure 4.	HP-8510B System Mounted on a Rack.....	9
Figure 5.	Performance Curves for the AEL H1498 Antenna....	12
Figure 6.	Masking of Panel with Radar Absorbing Material..	14
Figure 7.	Main-menu Function Keys.....	17
Figure 8.	Setup Sub-menu Function Keys.....	19
Figure 9.	System Signal Flow Diagram.....	23
Figure 10.	Target Raw Data.....	27
Figure 11.	Frequency Response after Background Subtraction .....	28
Figure 12.	Frequency Response after Calibration.....	29
Figure 13.	Frequency Response after Windowing.....	31
Figure 14.	Frequency Response after Adding Zeros and Conjugates.....	32
Figure 15.	Time Response after Shifting.....	34
Figure 16.	Frequency Response after Unwindowing.....	36
Figure 17.	Frequency Response of a 2.54 cm Diameter Sphere.....	40
Figure 18.	Time Transient Response of a 2.54 cm Diameter Sphere.....	41
Figure 19.	Frequency Response of a 7.94 cm Diameter Sphere.....	42



Figure 20.	Time Transient Response of a 7.94 cm Diameter Sphere.....	43
Figure 21.	Frequency Response of a 15.24 cm Diameter Sphere.....	44
Figure 22.	Time Transient Response of a 15.24 cm Diameter Sphere.....	45

### ACKNOWLEDGEMENTS

I would like to express my deep appreciation to Professor Michael A. Morgan, whose patience, sincere encouragement, and technical advise were indispensable in the completion of this thesis. Also, I would like to thank Dr. Dean Mensa at the Naval Air Warfare Center, Point Mugu who had reviewed the manuscript and offered numerous helpful suggestions. Thanks are also due to Professor David Jenn, my second reader, for his advise and encouragement. Last, but not least, I am greatly indebted to my wife, Sarah, and my children, Ernest and Julie, whose moral encouragement and personal sacrifice will be remembered in my heart forever.

## **I. INTRODUCTION**

### **A. BACKGROUND**

A radar detects targets at far distances by transmitting radio waves and listening for echoes resulting from fields scattered by the target. The scattered fields vary significantly with the radar frequency and polarization and with the target's shape, materials, and orientation. Knowledge of the scattering properties of potential targets is essential in designing and assessing performance of radar systems. On the other hand, scattering aspects of new military vehicle designs must be considered to enhance their survivability against enemy radars and weapons. Because radars play increasingly important roles in modern warfare, research to develop efficient and accurate techniques of measuring scattering properties of radar targets has become a high-priority task.

Given a knowledge of the incident wavefield, the electromagnetic properties of a radar target are completely described by the scattered wavefield. The strength of the scattered field is indicated by the target's radar cross section (RCS), a parameter widely used in the radar community. Although the RCS is a normalized scalar measure of the complex scattered wavefield, the term is often used to

describe the scattering characteristics of a target. Scattering responses of the target can be measured either in the time or frequency domain and the two responses are related by a Fourier transform.

The Transient Electromagnetic Scattering Laboratory (TESL) at the Naval Postgraduate School (NPS) currently utilizes a time domain technique to measure scattered fields. The system transmits short pulses and measures the target scattering response directly using a sampling oscilloscope. Time-domain techniques are considered faster, less expensive, and better suited to direct observations of transient scattering responses than frequency-domain techniques. However, frequency-domain techniques are considered more stable, less susceptible to noise, and capable of spanning a wider measurement frequency range.

## **B. OBJECTIVE**

The objective in this thesis research is to develop a capability for measuring frequency-domain scattered fields over the 2 to 18 GHz range. The effort consists of installing and integrating an HP-8510B network analyzer system, mounting antennas on a wall panel in an anechoic chamber, installing an HP-IB controller in a personal computer, writing an HP BASIC program for remote system control and data acquisition, creating a MatLab signal processing algorithm for background subtraction, calibration

and transformation to the time domain, and conducting RCS measurements on simple targets for validation. The new frequency-domain system will complement the existing time-domain RCS measurement system and should yield similar results when frequency-domain data are transformed into the time domain. Measurement validations for complex targets will be possible through comparing time and frequency-domain results acquired independently.

The thesis is divided into six chapters. Chapter II illustrates the system and measurement setup. Detailed descriptions are given for the anechoic chamber, the HP-8510B network analyzer, and the antennas. Chapter III explains the system control and data acquisition including controller hardware, data acquisition software, and measurement procedures. Chapter IV describes signal processing software for background subtraction and calibration. Fast Fourier Transform (FFT) techniques to recover time transient responses from frequency domain data are discussed, in addition to important processing aspects of windows, conjugation, and zero padding. Chapter V addresses system validation by presenting results of measurements on different size spheres. Finally, conclusions and future considerations are presented in Chapter VI.

## II. SYSTEM DESCRIPTION AND MEASUREMENT SETUP

### A. OVERVIEW

The frequency-domain scattered field measurement system, depicted in Figure 1, is implemented on an HP-8510B network analyzer [Ref. 1] using its stepped frequency mode. The system consists of an HP-8340B synthesized sweeper as an RF source, an HP-8511A frequency converter as an RF front end, an HP-8510B network analyzer as an IF receiver, AEL H1498 multi-octave horns serving as transmitting and receiving antennas, and an IBM PC-compatible computer with HP-82300C BASIC Language Processor as a data acquisition workstation and remote system controller.

System components are selected for scattered field measurements of 2 to 18 GHz. The system operates by spanning the frequency band with 801 steps. The maximum number of frequency steps allowed by the analyzer is used to maximize the unambiguous time extent.

For each frequency step, the system is phase-locked and continuous-wave (CW) signals are transmitted through the transmitting antenna in an anechoic chamber. The RF energy reflected by the target is collected by the receiving antenna, and initially down-converted to 20 MHz using a harmonic mixer in the frequency converter, followed by a

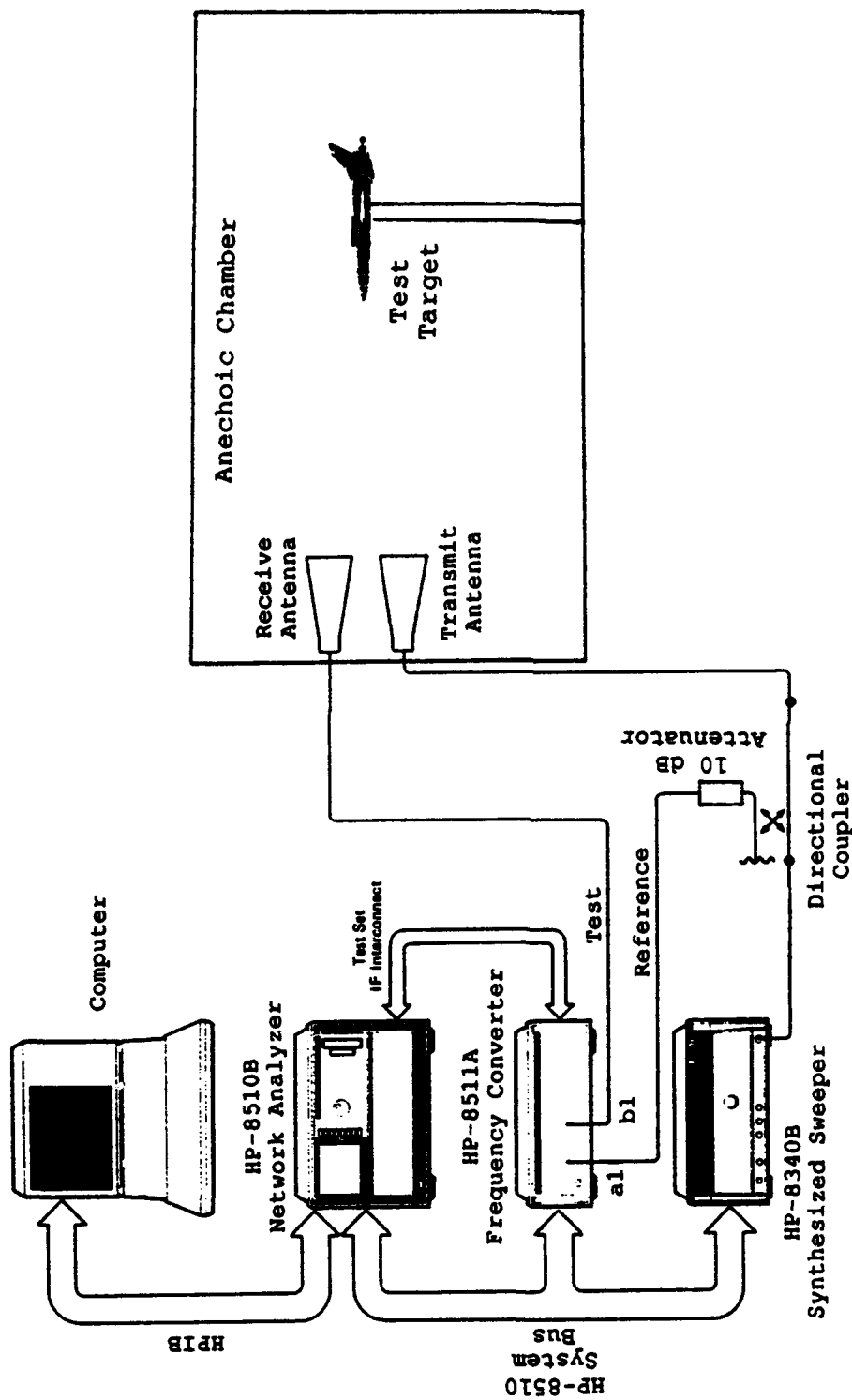


Figure 1. Schematic Drawing of the Frequency Domain Scattered Field Measurement System Implemented on the HP-8510 Network Analyzer. [Ref. 1]

second mixer which produces an IF frequency of 100 KHz for subsequent analog-to-digital (A/D) conversion. This IF signal is processed through the "b1" channel in the frequency converter. For coherent detection with phase information, a constant RF signal is coupled using a 22 dB directional coupler at the RF source and down-converted through the "a1" channel. Amplitude and phase information for the specific frequency are established by comparing the "b1" channel (signal channel) to the "a1" channel (reference channel). The HP-8510B periodically sends a command to the synthesizer to change to the next frequency step until all 801 frequencies are measured.

The magnitude and phase data for 801 frequencies are transferred from the HP-8510B to the computer over the GPIB bus, stored on the internal hard disk, and subsequently processed with a digital signal processing algorithm written in MatLab.

## **B. SYSTEM DESCRIPTION**

### **1. Anechoic Chamber**

The anechoic chamber, shown in Figure 2, is located in room 535 of Spanagal Hall, measures 3.1 x 3.1 x 6.2 meter in height, width, and length and is shielded using aluminum sheet metal. Antennas mounted on the source wall illuminate targets supported on a low-density styrofoam column positioned 2.3 meters away. The source wall is covered with



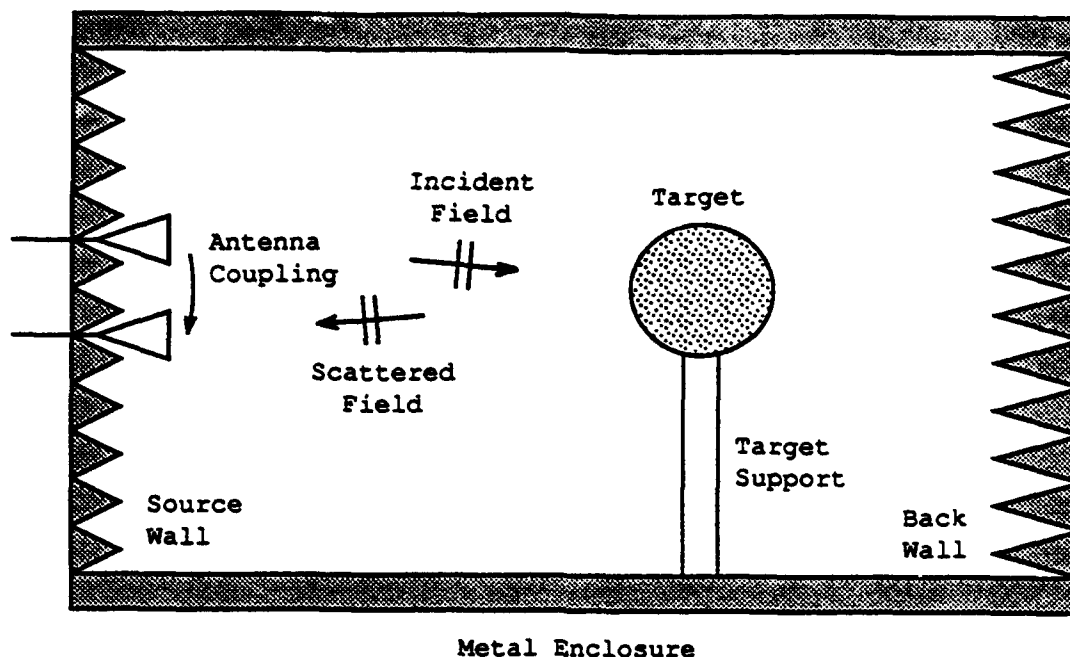


Figure 2. General Layout of the Anechoic Chamber

21 cm pyramidal radar absorbing material (RAM) and the back wall is covered with 46 cm pyramidal RAM. Sidewalls, floor, and ceiling are covered with longitudinal wedge RAM to direct energy towards the absorbing back wall. Figure 3 shows the chamber interior looking from the back wall. Further details of the chamber can be found in References 2 and 3.

## 2. HP-8510B Network Analyzer

The HP-8510B network analyzer, shown in Figure 4, is a high-performance measurement instrument designed to make microwave measurements of many kinds. In the course of this thesis effort, the HP-8510B network analyzer was configured as a phase-locked scattered field measurement system that

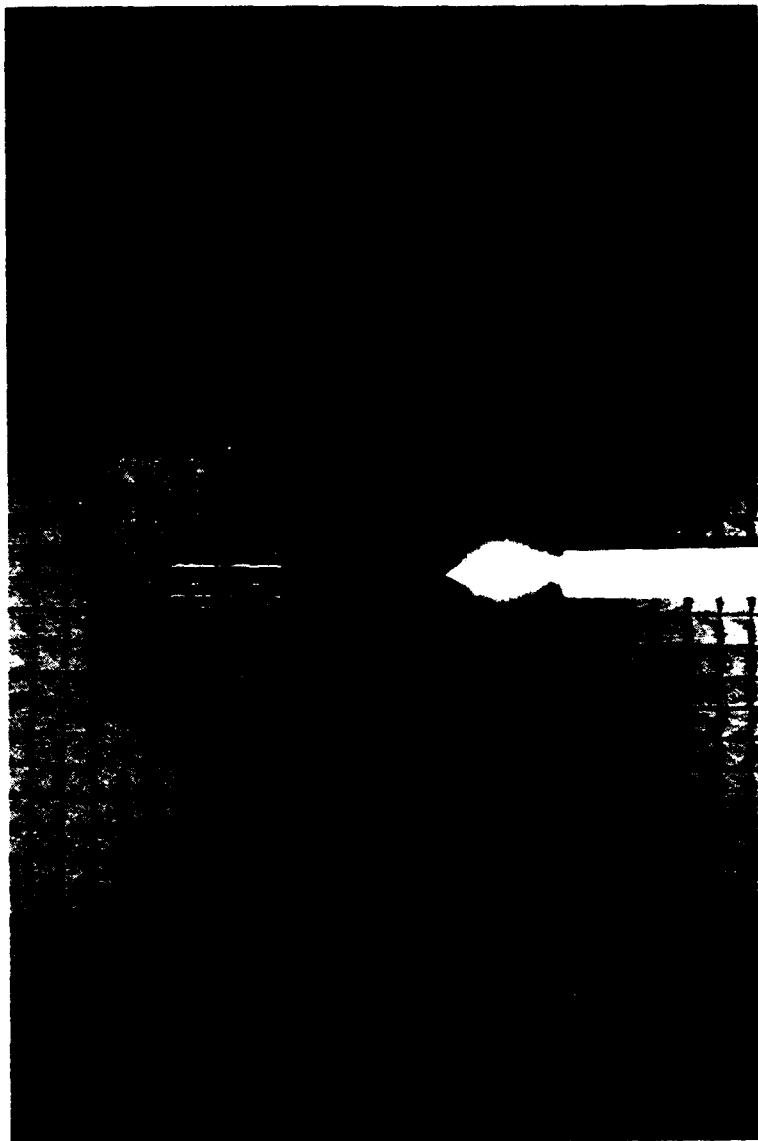


Figure 3. Interior of the Anechoic Chamber

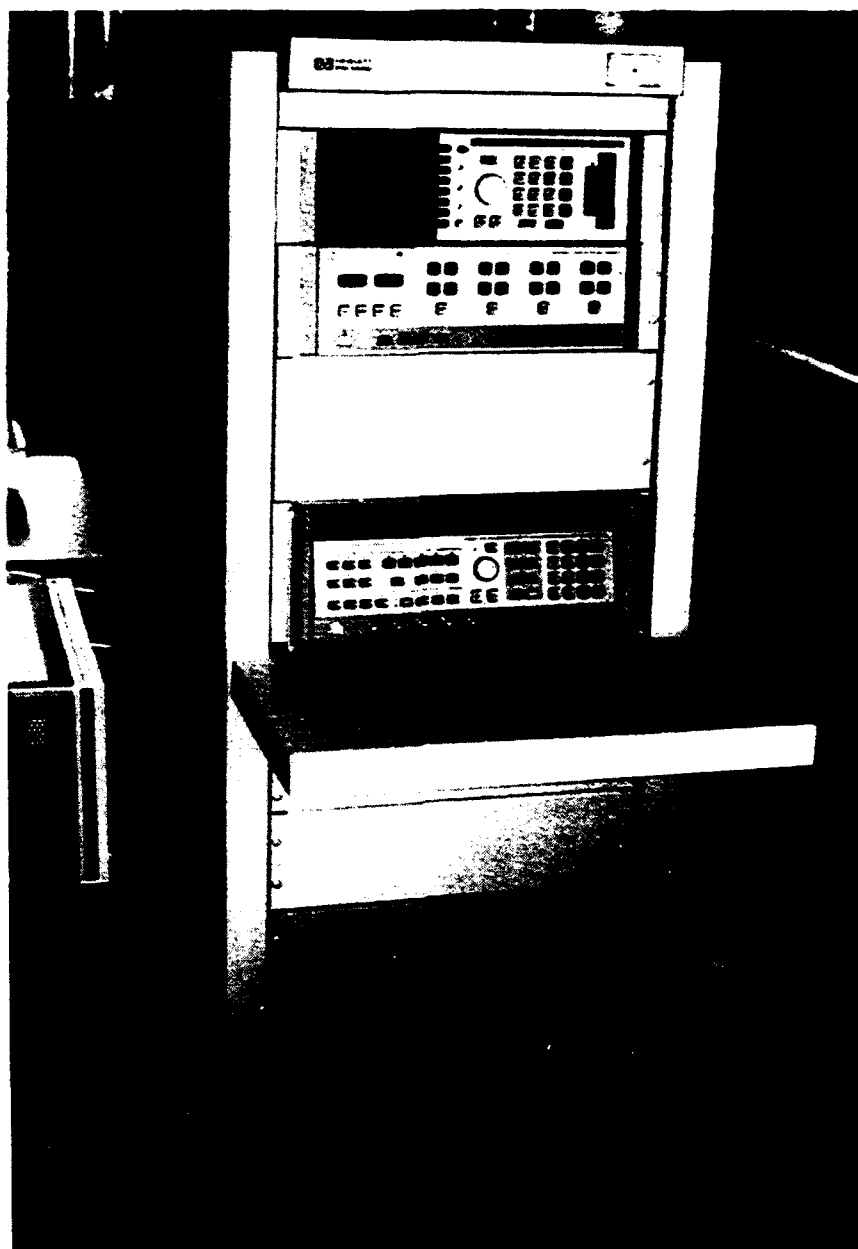


Figure 4. HP-8510 System Mounted on a Rack

offers very broad frequency coverage, wide dynamic range, and high measurement sensitivity. The HP-8510B network analyzer system consists of a microwave source (HP-8340B), RF front end (HP-8511A), and the HP 8510B as IF receiver and system controller. The HP-8510B controls the RF source and test set over a dedicated HP-8510B system bus. The HP-8511A RF front end provides a broad bandwidth of 45 MHz to 26.5 GHz and wide dynamic range of 75 to 105 dB, depending on averaging factor. The HP-8511A uses a harmonic sampling technique to convert the RF signals at its two inputs to 20 MHz IF signals that are subsequently processed by the HP-8510B.

In manual operation, the front panel keys of the HP-8510B are used to define measurement parameters and control the measurement process. In remote operation, the personal computer controls the HP-8510B by sending commands over the HP-IB bus to execute the measurement process.

To measure amplitude and phase, the HP-8510B must have a reference signal that remains constant during the measurement. The phase-locked reference signal is obtained using an HP-11691D 20 dB, 2-18 GHz directional coupler inserted between the HP8340B RF source and the transmitting antenna. The measured amplitude and phase data are transferred to the personal computer over an HP-IB bus.

For wideband scattered field measurements, the HP-8510B network analyzer can operate either in RAMP mode or in STEP mode. In RAMP mode, the source is swept in a continuous

analog sweep from the lower to upper frequency and the data is sampled without stopping the sweep. In STEP mode, the source is tuned and phase-locked to each of the 801 frequency sample points. The STEP mode is more stable in terms of frequency accuracy and source power level than the RAMP mode. The STEP mode will be used in all results of this thesis.

### 3. Antennas

AEL H1498 multi-octave horns [Ref. 4] are used for transmit and receive antennas to meet wideband requirements. This coaxially-fed, double-ridged horn antenna covers the 2-18 GHz frequency band. Average electrical characteristics are listed in Table 1 and performance over the 2-18 GHz frequency range is shown in Figure 5.

TABLE 1. ELECTRICAL CHARACTERISTICS OF AEL H1498 ANTENNA

Frequency (GHz)	VSWR	Avg. Gain (dBi)	Avg. 3dB Beamwidth		Max. Power (Watts)
			E Plane	H Plane	
2 - 18	2.5:1	11	50°	45°	50

The antennas are mounted on a 24-inch square wood panel covered with aluminum sheet which is tightly fitted into a square opening in the source wall. The panel is covered with the same radar absorbing material as the source wall to eliminate multi-path effects between the antennas and the panel. The antennas are displaced vertically with the E-plane in the horizontal direction to minimize coupling. They are shimmed to point the beam at the target to minimize

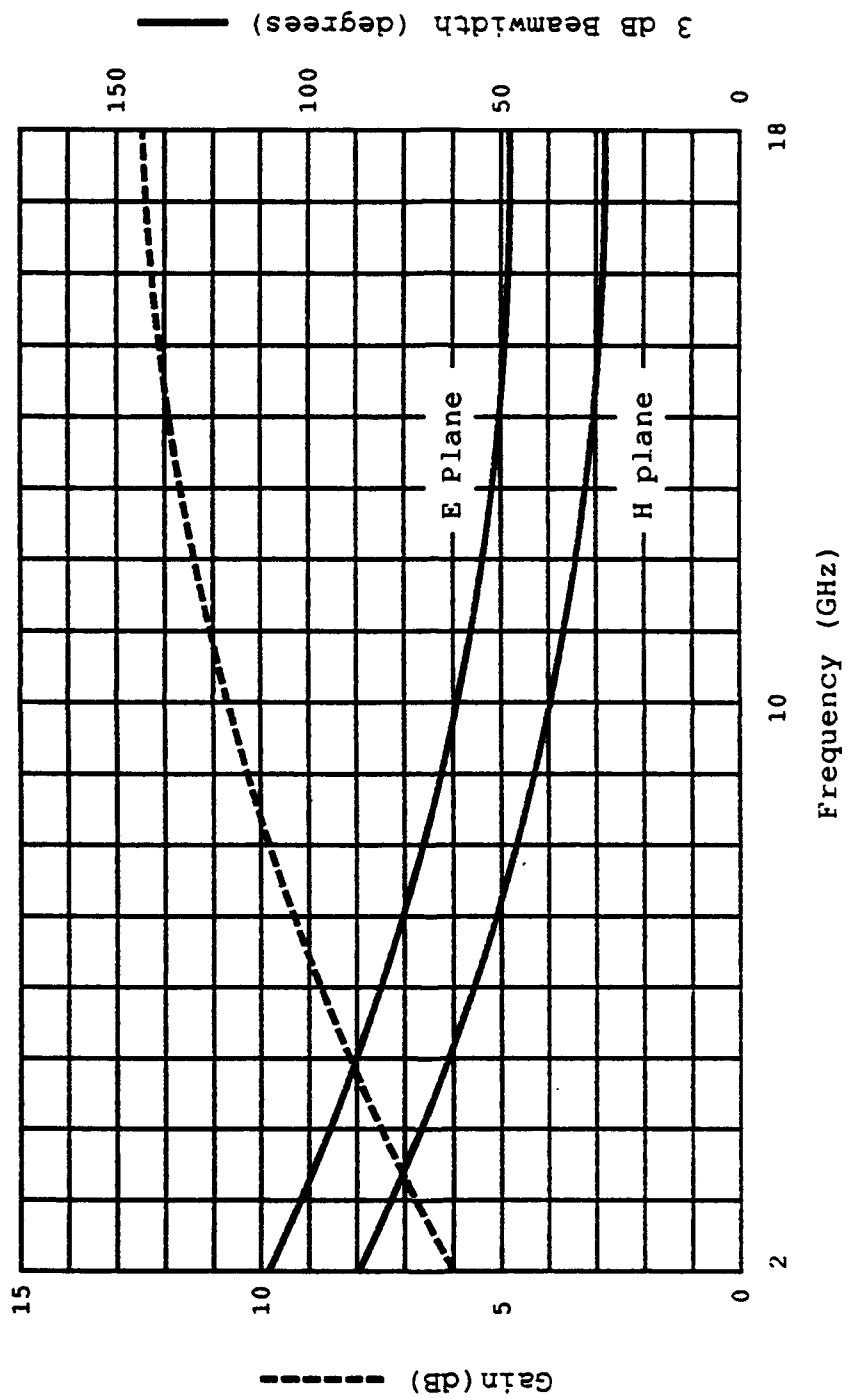


Figure 5. Performance Curves for the AEL H1498 Antenna. [Ref. 4]

boresight errors. Figure 6 shows the panel covered with RAM material.

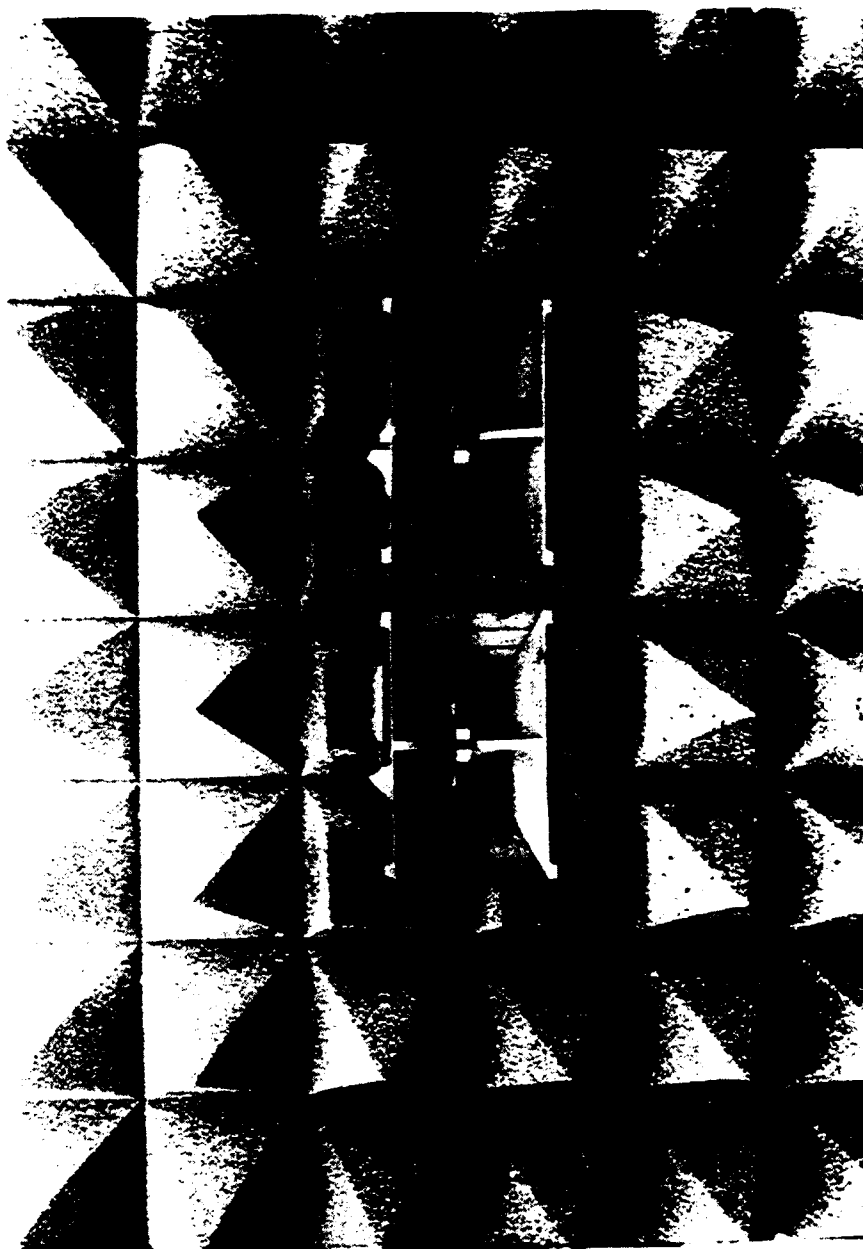


Figure 6. Masking of Panel with Radar Absorbing Material



### **III. REMOTE CONTROL AND DATA ACQUISITION**

#### **A. REMOTE CONTROLLER HARDWARE**

The HP-8510B is used to define measurement parameters and control the measurement process; it can be operated manually with front panel keys or remotely through an HPIB bus. In remote operation, measurement parameters such as frequency range, number of frequency points, and averaging factor, can be set from a computer by sending proper commands on the HPIB bus. A COMPAQ Deskpro-386 computer using an HP-82300C BASIC Language Processor [Ref. 5] with a built-in HPIB interface was chosen as a remote system controller.

The HP-82300C BASIC Language Processor consists of an MC68000 processor card, HP-BASIC interpreter, emulator software, 4 megabytes of RAM memory, and a built-in HPIB interface. The processor card fits into a standard 16 bit ISA slot of the computer. The HP-BASIC interpreter and emulator software provide the capabilities of an HP-300 BASIC workstation while retaining all the capabilities of MS-DOS. Bi-directional communication between HP-BASIC and DOS applications allows data acquired by BASIC to be stored in DOS ASCII format on the PC hard disk.

## B. CONTROL AND DATA ACQUISITION SOFTWARE

Control and data acquisition software, named "GET\_DATA", is written in HP-BASIC and runs on the HP-82300C BASIC Language Processor within the PC. The software controls the HP-8510B, acquires measured data through the HP-IB bus, and writes this to the PC hard disk.

After the PC is booted up, the user types "cd blp" to change to the blp directory. The name "blp" stands for basic language processor, and is a default name given when the BASIC Language Processor is installed. The user then types "basic" to cause the HP-BASIC interpreter to run on the PC. From this point, the PC runs as an HP-300 BASIC workstation, and the user issues HP-BASIC commands until quitting HP-BASIC by typing "[control]-F10" and returning to the DOS environment.

When HP-BASIC runs, the user types "LOAD "GET\_DATA"". This BASIC command loads the program from the hard disk to RAM. When the user types "RUN", the program executes and takes over control of the HP-8510B. The preceding executions are summarized as follows:

```
c:\> cd blp
```

```
c:\BLP> basic
```

```
LOAD "GET_DATA"
```

```
RUN
```

When the "GET\_DATA" program runs, the computer CRT displays the main-menu function keys at the bottom and the current HP-8510B status parameters such as start frequency, stop frequency, number of frequency points, RF source power level, sweep mode, active calibration set, and averaging factor at the top. The user can recall a default setup and start measurements by pressing appropriate function keys.

The main-menu function keys are shown in Figure 7, and their function is described below.



Figure 7. Main-menu Function Keys

**Continu. Sweep** - Pressing this function key causes the HP-8510B to sweep continuously through the 801 frequency points, to transmit RF energy and update data.

**Single Sweep** - Pressing this function key causes the HP-8510B to start sweeping from the first frequency point to the last frequency point. When the single sweep is completed, the RF transmission is shut off and the data are stored in the HP-8510B until the "Continu. Sweep" key or "Single Sweep" key is pressed for new data.

**Hold Sweep** - Pressing this function key halts the frequency sweeping and shuts off RF transmission.

**Change  
#Average**

- Pressing this function key alters the averaging used to increase signal-to-noise ratio. In STEP mode, averaging is done at each frequency as the HP-8510B steps through the 801 frequency points. The averaging factor can range from 1 to 4096. The measurement time increases proportionally as the averaging factor increases. The data in the results section were measured with the averaging factor of 128.

**Record  
Data**

- Pressing this function key causes the writing of two data files. The first file begins with a letter "D" and is in a DOS ASCII format, the second file begins with a letter "F" and is in an HP-BASIC binary format. The contents of these two files are exactly the same. Each line of 801 rows lists a frequency index, magnitude in dB, and phase in degrees. After two plots are drawn on computer CRT, the program is paused until a "continue" function key is pressed to resume.

**Playback  
Data**

- Pressing this function key allows a user to retrieve old data and display them on a computer CRT. The program reads the HP-BASIC binary format file.

**Change  
Setup**

- Pressing this function key allows the user to change measurement parameters on the HP-8510B remotely.

**Default Setup**

- Pressing this function key sets measurement parameters to default values. The default values are 2-18 GHz, 801 frequency points, STEP mode, continuous sweep, a source power of 10 dBm, and an averaging factor of 16.

When the "Change Setup" function key is pressed, a setup sub-menu will be displayed. The function keys for the setup sub-menu are shown in Figure 8.



Figure 8. Setup Sub-menu Function Keys

**Save State**

- Pressing this function key saves a complete HP-8510B state into a storage register in the HP-8510B. All measurement parameters are included in the saved state.

**Recall State**

- Pressing this function key recalls a saved state.

**Change Freq**

- Pressing this function key allows the user to change frequency range.

**No. of Point**

- Pressing this function key allows the user to set the number of frequency points to 51, 101, 201, 401 or 801.

**Power Level**

- Pressing this function key allows the user to set the power level of the RF source.

**Sweep Mode**

- Pressing this function key allows the user to

select either STEP mode or RAMP mode.

**Calibra-  
tion**

- Pressing this function key activates the HP-8510B internal error correction feature.

**Go to  
Mainmenu**

- Pressing this function key causes the main menu to be displayed.

The program can be stopped by pressing "[shift]-pause". The source code may be edited by typing "EDIT". The program must be stopped before "EDIT" is executed. Further details of the HP-BASIC programming can be found in Reference 1, and the "GET\_DATA" source code can be found in Appendix A.

### **C. MEASUREMENT PROCEDURES**

The first step is to power up the HP-8510B system and boot up the computer and allow a 30-minute warm-up for the synthesizer. Next, load the "GET\_DATA" program. When the program runs, press the "Default Setup" function key to set the HP-8510B to a default setup. Use the "Change Setup" key to change the setup. For the data in this thesis, the default setup is first recalled, and then the averaging factor is changed to 128.

When the setup is completed, press "Hold Sweep" key to halt RF radiation. This step may be skipped if the user believes the RF radiation level is not a health hazard.

All measurements require three steps: calibration, background, and target scattering. In the first step, place a metallic sphere calibration target on the target column. Press "Single Sweep" key. Sweeping through all 801 points takes 40 seconds to 200 seconds depending on the averaging factor. When sweeping is done, press "Record Data" key. When two plots are displayed, press "Continue" key and type in a number such as 123 for filenames of "D123.DAT" and "F123.DAT". The input statement is programmed to accept only numeric inputs and not alphanumerics. If the user desires other names, the DOS "rename" command can be used in the DOS environment after the data acquisition program is terminated. Remove the calibration target, and measure the background by pressing the "Single Sweep" key. Press the "Record Data", and assign a new number to the background data. Then, place the target on the column and repeat the single sweeping and recording for the target data.

Three data files have been saved on the PC hard disk: calibration, background, and target. These files will be subsequently processed by the MatLab program. If more target measurements are required, the preceding three steps can be repeated for a new target, using new names for the stored files.

## **IV. POST-PROCESSING**

### **A. ALGORITHM OVERVIEW**

The RCS of a target is a function of frequency, polarization, and target orientation and should be independent of measurement instrumentation and anechoic chamber conditions. However, the raw data obtained from RCS measurements contains unwanted effects such as noise, antenna coupling, chamber clutter, antenna gain, and distance to target.

The unwanted effects fall into two groups; the first is caused by extraneous signals such as noise, antenna coupling and chamber clutter, and the second is caused by the dependence of the measurement system on transmitting power level, cable loss, antenna gain, distance to target, and receiver mixer performance. In an ideal case, the receiver output in the absence of the target should be zero. Due to residual scattering of chamber RAM and significant coupling between the transmitting and receiving antennas, however, an undesirable background signal exists in all measured data. This undesirable signal can be removed by measuring the background data and performing a complex subtraction from the target data. The dependence on the measurement system can be removed by measuring a calibration sphere of known scattering



characteristics and the target of interest and forming the ratio of the measured responses multiplied by the computed field response of the calibration sphere.

Once the frequency domain scattered fields of the target are established by the background subtraction and calibration process, transient time responses are obtained through an inverse Fourier transform. For a time transient response using efficient inverse FFT, complex conjugates and zeros are appended to the frequency-domain data, as will be shown. Finally, time-gating the transient response around the target and Fourier transformation back to the frequency domain smoothes out the frequency data and provides refined RCS levels.

#### B. BACKGROUND SUBTRACTION AND CALIBRATION

Operation of the measurement system is represented by the signal flow diagram in Figure 9. The RF excitation is

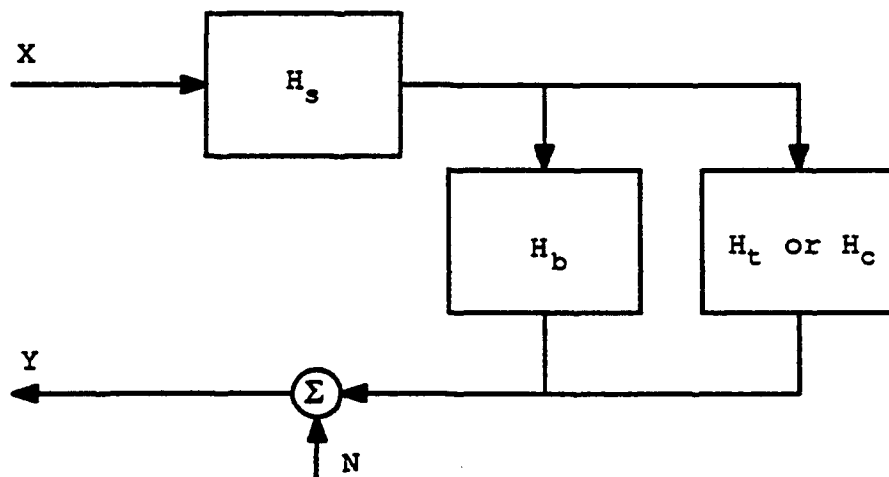


Figure 9. System Signal Flow Diagram

denoted by X, and the signal out of the network analyzer by Y. The symbol,  $H_S$ , represents the transfer function of combined measurement system dependence which includes RF cable loss, both antenna characteristics, two-way free-space loss from antennas to target, and RF mixer conversion loss. The symbol,  $H_T$ , is the frequency response of the target, and  $H_C$  is that of the calibration sphere. Both  $H_T$  and  $H_C$  are the ratios of the scattered field at the location of the receiving antenna to the incident field at the location of the scatterer, multiplied by the one-way free-space spread factor, as defined in Equations (1) and (2).

$$H_T = R (4\pi)^{1/2} \frac{E^s \text{ (at the receiving antenna)}}{E^i \text{ (at the target)}} \quad (1)$$

$$H_C = R (4\pi)^{1/2} \frac{E^s \text{ (at the receiving antenna)}}{E^i \text{ (at the calibration sphere)}} \quad (2)$$

where  $H_T$  = frequency response of target  
 $H_C$  = frequency response of calibration sphere  
 $E^s$  = scattered electric field  
 $E^i$  = incident electric field  
 $R$  = distance from the receiving antenna to the target

Background errors such as antenna coupling and chamber clutter are grouped together and denoted by  $H_b$ . The chamber thermal noise and receiver mixer noise are denoted by  $N$ .

Equations (3)-(5) can be written from the signal relationship.

$$Y_t = X H_s (H_t + H_b) + N_t \quad (3)$$

$$Y_b = X H_s (0 + H_b) + N_b \quad (4)$$

$$Y_c = X H_s (H_c + H_b) + N_c \quad (5)$$

where  $Y_t$  = signal out of network analyzer in target measurement  
 $Y_b$  = signal out of network analyzer in background measurement  
 $Y_c$  = signal out of network analyzer in calibration sphere measurement  
 $X$  = RF excitation  
 $H_s$  = frequency response of measurement system dependency  
 $H_b$  = frequency response of background

An estimator of the frequency response of the target,  $H_{te}$ , can be derived by a simple algebraic manipulation of Equations (3)-(5). This will be termed the calibration process.

$$H_{te} = H_{cc} (Y_t - Y_b) / (Y_c - Y_b) \quad (6)$$

The estimator becomes exact as the measurement noise approaches zero.

As shown in Equation (6), the target frequency response can be calculated from the three measured data and the computed frequency response of the calibration sphere,  $H_{cc}$ . The measurement system dependency,  $H_s$ , cancels out in

deriving Equation (6). From the definition in Equation (1), the radar cross section,  $\sigma$ , is given by

$$\sigma = |H_t|^2 \quad (7)$$

Raw data taken from the network analyzer,  $Y_t$ , is shown in Figure 10. The antenna coupling is substantially larger than the target scattering at the lower frequencies so that the background signal dominates over the target signal. Figure 11 shows the target scattering after the background is subtracted out; the antenna coupling and chamber clutter are eliminated. The measurement system dependency is removed in the calibration process of Equation (6), and the result is shown in Figure 12. The spikes in the data are caused by a residual antenna coupling and chamber clutter, and will be greatly reduced by time-domain gating to be discussed in the following section.

## C. DIGITAL SIGNAL PROCESSING

### 1. Window Shape

The frequency-domain data are weighted with a window function prior to inverse FFT in order to reduce sidelobes in the time domain. Among many window shapes available in the MatLab signal processing library, the Hamming window [Ref. 6], which is a raised cosine function, was determined to be best suited because the effects of windowing can be removed by multiplying the data with an inverse of the window

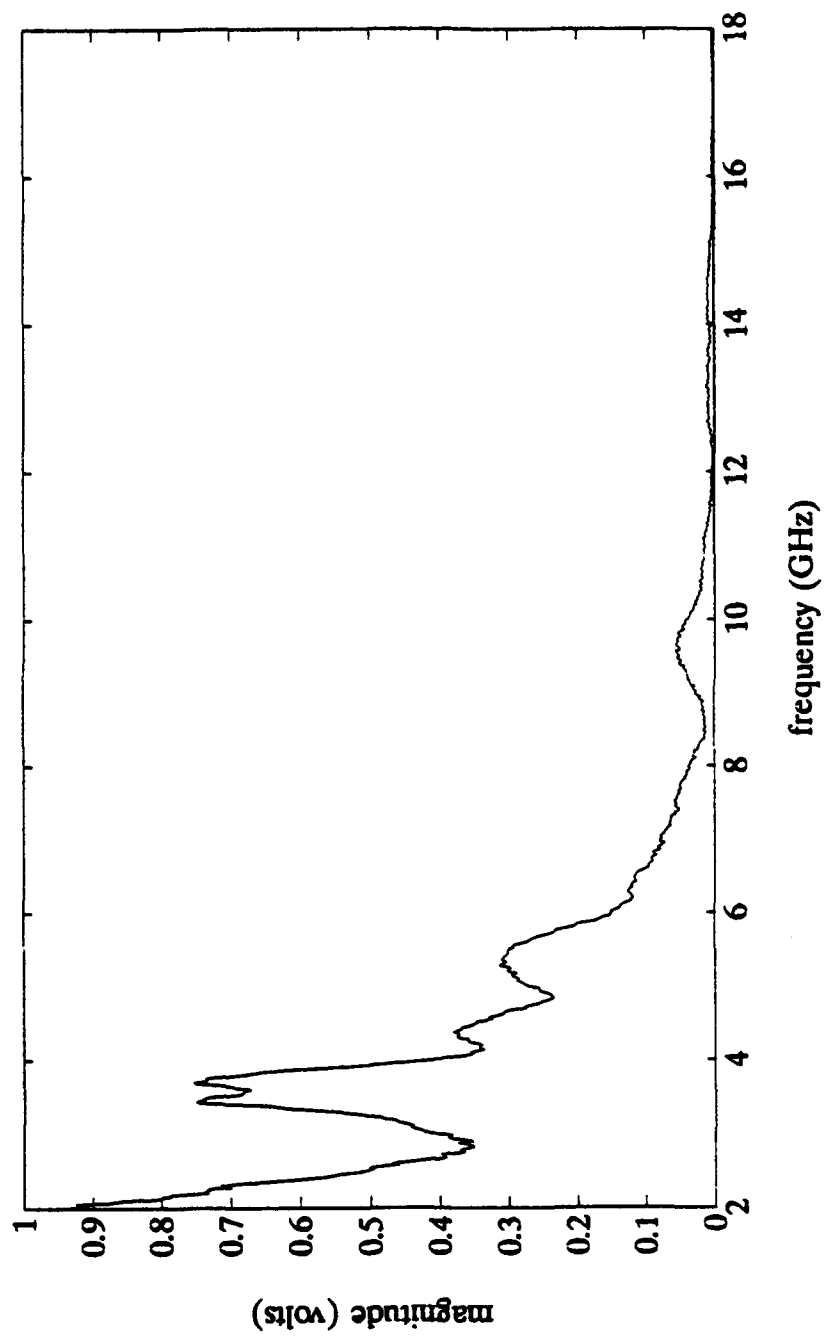


Figure 10. Target Raw Data

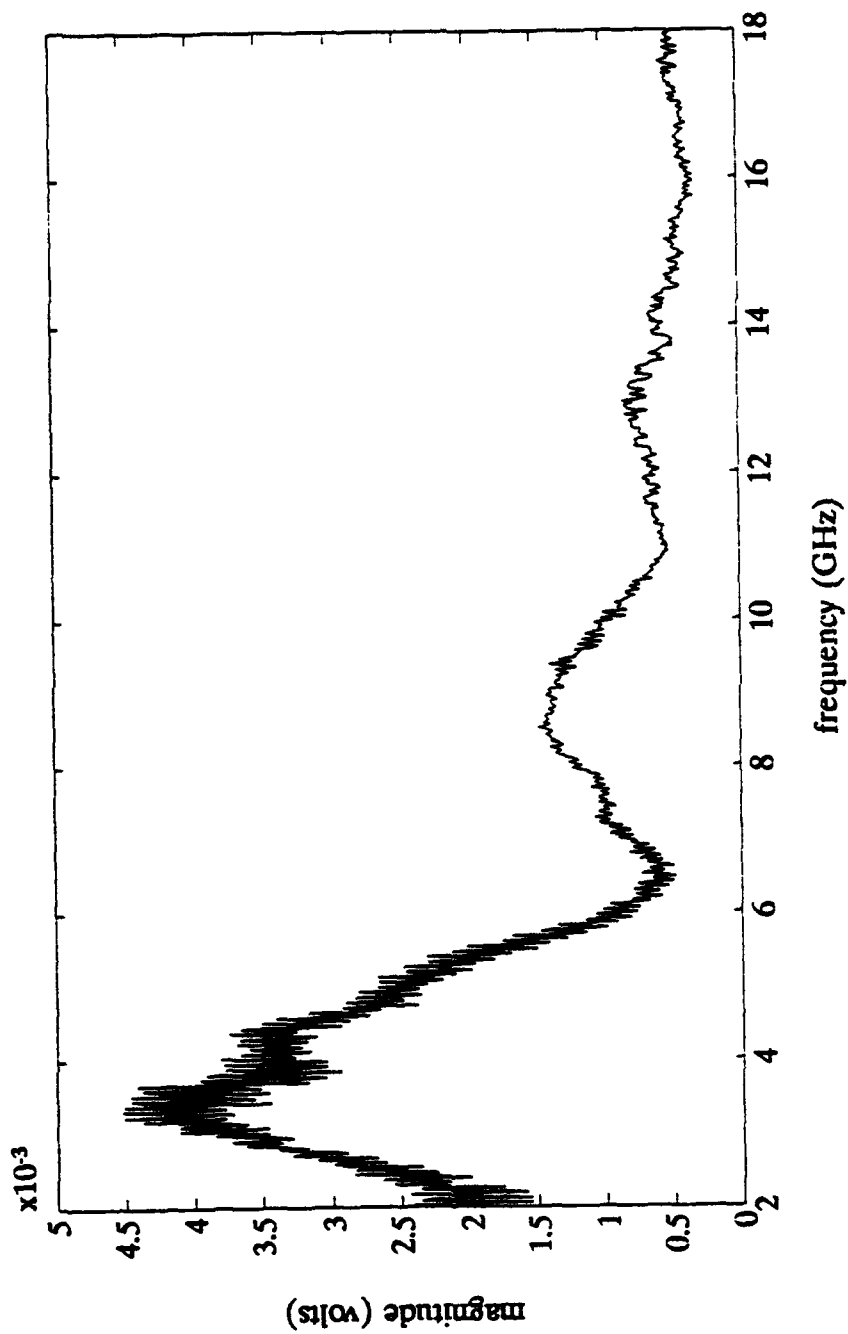


Figure 11. Frequency Response after Background Subtraction

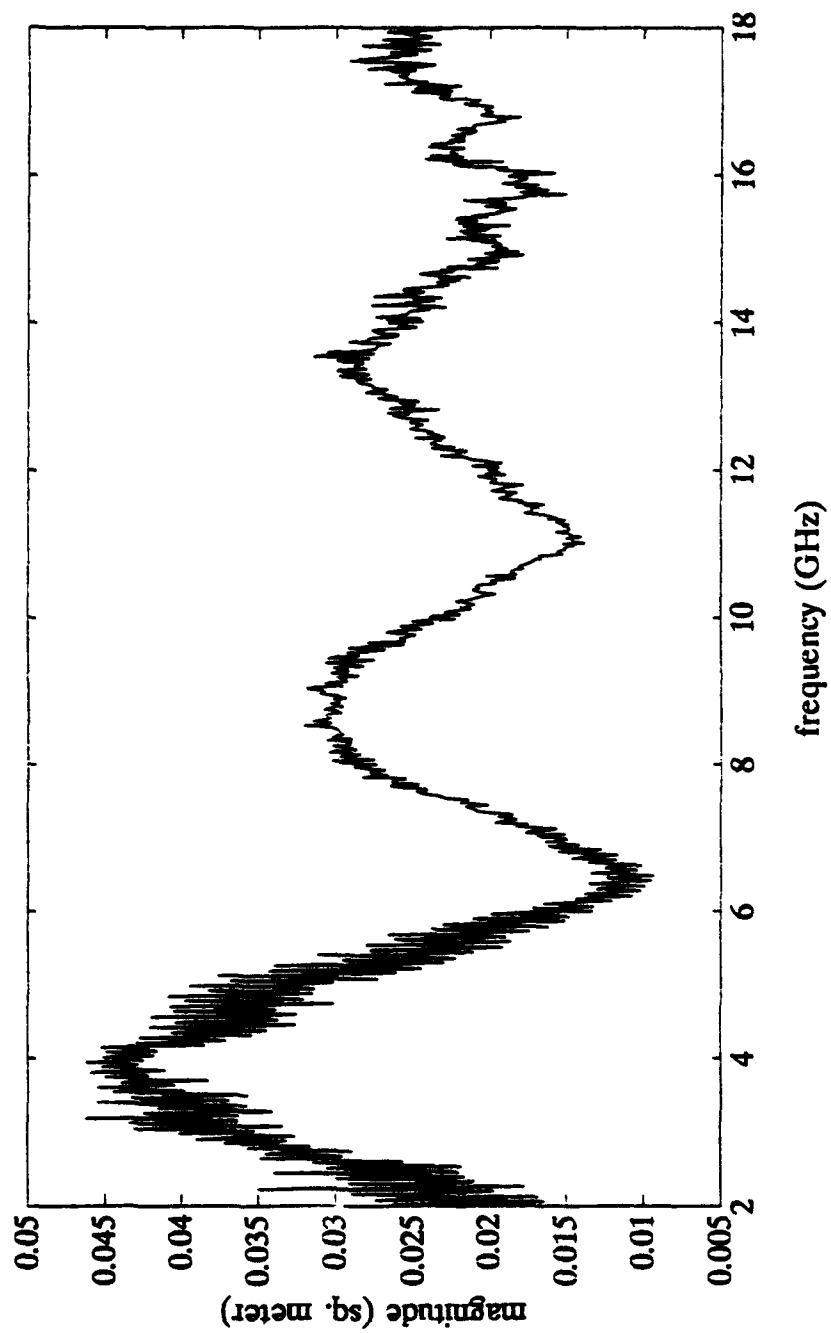


Figure 12. Frequency Response after Calibration

function. Other windows have zero end values so that the inverse can not be taken. The actual equation of the Hamming window in the library is given in Equation (8).

$$W = 0.54 - 0.46 \cdot \cos(2 \cdot \pi \cdot n / (N-1)) \quad (8)$$

where     $W$  = weighting factor in the window function  
          $N$  = total number of sample points  
          $n$  = index ranging from 0 to  $N-1$

The data in Figure 12 are Hamming-windowed and shown in Figure 13.

## **2. Zero-padding and Complex Conjugate**

After the data are weighted with the Hamming window function, 100 data points with zero value are inserted in front of the windowed data to fill in the missing DC-2GHz data, and 123 zeros are appended to the end of the data to make the total number of data points 1024, thus allowing use of radix-2 FFT algorithm. The complex conjugates of the 1024 data points are added, making a total of 2048 data points. The complex conjugate is necessary to make the transformed time-domain data a time transient response. The layout of the 2048 data points is illustrated in Figure 14.

## **3. Fourier Transforms, Gating and Unwindowing**

The 2048 data points in the frequency domain are transformed to the time domain with an IFFT routine in the MatLab library. The routine,  $\text{IFFT}(X)$ , is the inverse discrete Fourier transform of vector  $X$ . The IFFT employs a



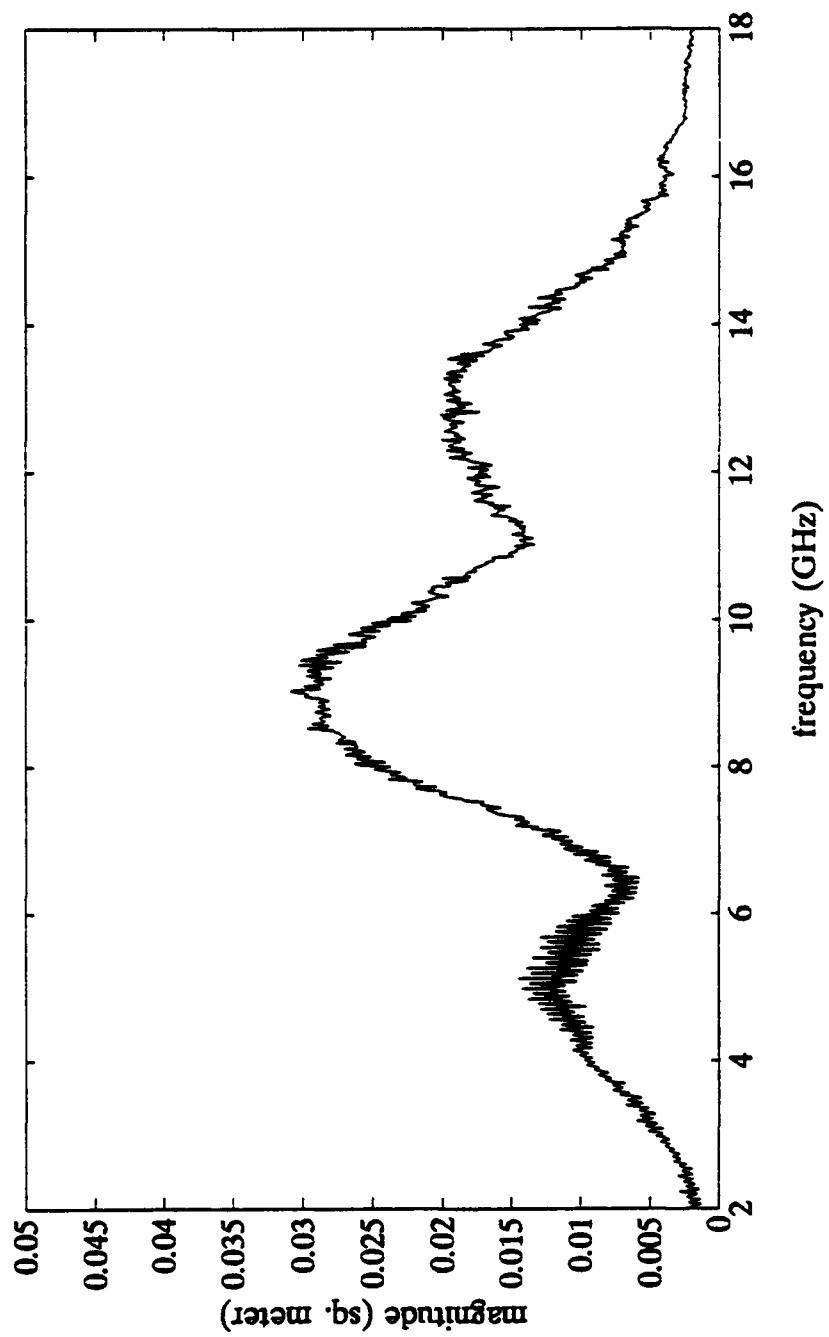


Figure 13. Frequency Response after Windowing

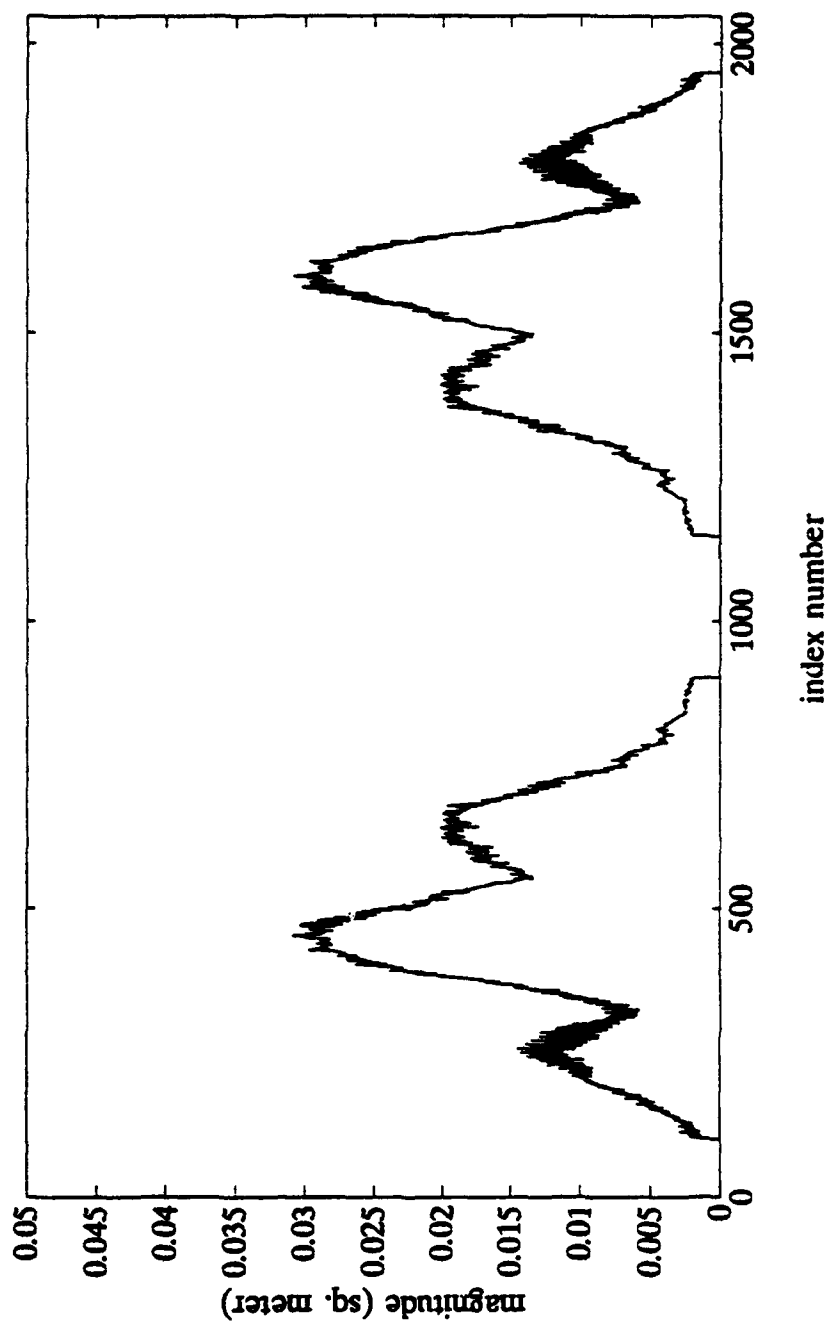


Figure 14. Frequency Response after Adding Zeros and Conjugates

fast radix-2 algorithm when the length of X is an integer power of two, and a slower algorithm when the length of X is not a power of two. The IFFT operation performed on the 2048 complex data points yields another set of 2048 complex numbers of which the imaginary part is zero, and the real part represents the time transient response.

In the time-domain plot, the position where the target appears depends on the phase reference in the computation of the calibration sphere. In order to place the antenna coupling at time zero and thus make the time transient response plot easier to read, the data are shifted 589 cells as shown in Figure 15. The wrap-around nature of the Fourier transform output permits the shifting of data without any loss or discontinuity. Shifting data in the time domain is equivalent to multiplication in the frequency domain by a linear phase term and does not affect the magnitudes.

After shifting, the time domain data are gated to remove residuals of antenna coupling and any return from the chamber which has not been eliminated completely in the background subtraction. The gate is centered at the 600th cell, and the width is 400 cells. The gate is centered on the target, and the gate width corresponds to approximately 10 nanoseconds.

The gated data are transformed back to the frequency domain with an FFT routine in the MatLab library. Because

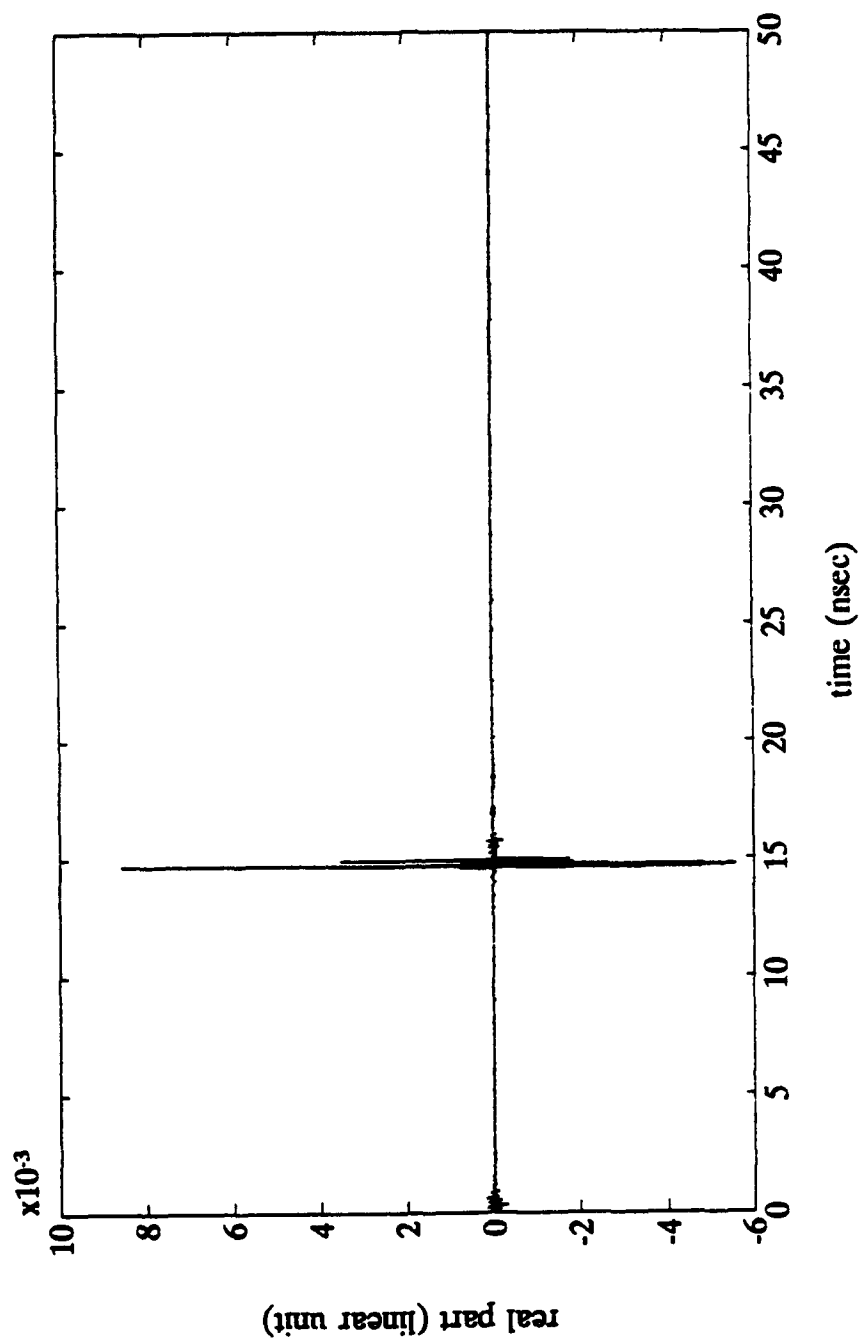


Figure 15. Time Response after Shifting

zeros and conjugates have been appended to the frequency data, the 801 data points between the 101st cell and the 901st cell represent the 2-18 GHz frequency range. Finally, an inverse of the Hamming window is applied to the 801 data points to remove the effect of windowing. The final data are shown in Figure 16 and the sharp spikes in Figure 12 are eliminated.

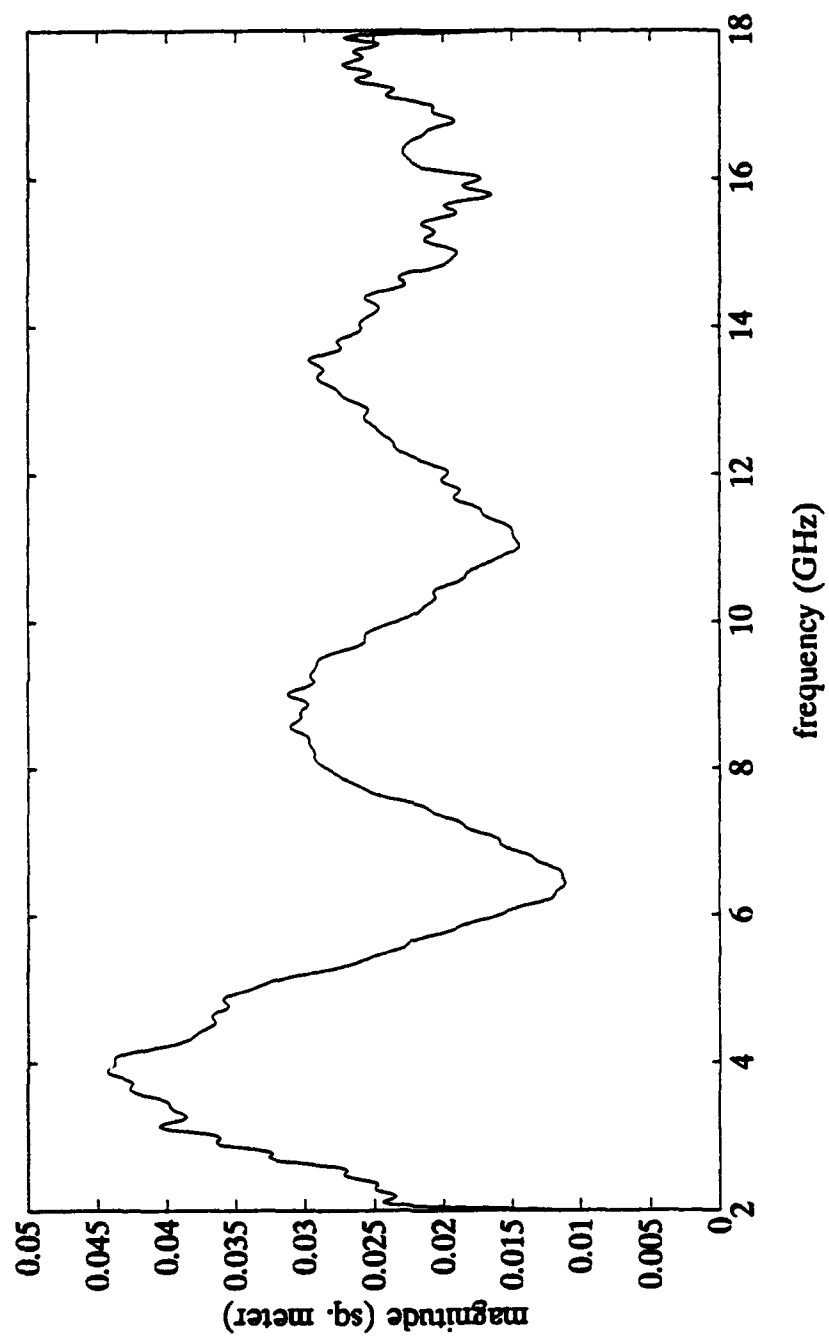


Figure 16. Frequency Response after Unwinding

## **V. SYSTEM VALIDATION**

### **A. CANONICAL TARGETS**

A set of metal spheres was measured in the NPS TESL anechoic chamber in order to validate the fidelity of the frequency-domain scattering measurement system. Metal spheres were chosen as validation targets because: 1) the exact solution is readily available from the Mie series solution, 2) the RCS is aspect-independent so that errors in target positioning are negligible, and 3) the time transient response exhibits a delayed creeping wave which can be used to validate the time-domain transformation.

The computer program, MIE.BAS written by M. Morgan for the Mie series solution [Ref. 2], has been modified and named MIE2.BAS. Since the original MIE.BAS calculates the scattered field observed at the receiving antenna, the free-space spread factor defined in Equation (2) has been added to the new MIE2.BAS program. The output of MIE2.BAS is used in the post-processing program, PROC.M, for calibrating the measured data by supplying the  $H_{CC}$  in Equation (6).

### **B. EXPERIMENTAL RESULTS**

A series of scattering measurements was performed on metal spheres in the frequency range of 2 to 18 GHz. The spheres were 15.24, 12.07, 7.94, and 2.54 centimeters(cm) in

diameter. Setup of the HP-8510B was in STEP mode sweep, 801 points, and averaging factor of 128. Antennas were oriented for horizontal polarization. The 12.07 cm sphere was arbitrarily chosen as a calibrator and the other spheres as targets. A test matrix is summarized in Table 2.

TABLE 2. TEST MATRIX OF SCATTERING MEASUREMENTS

Filename	Type	Descriptions
d101.dat	calibration	12.07 cm diameter sphere
d102.dat	background	empty chamber
d103.dat	target	2.54 cm diameter sphere
d104.dat	calibration	12.07 cm diameter sphere
d105.dat	background	empty chamber
d106.dat	target	7.94 cm diameter sphere
d107.dat	calibration	12.07 cm diameter sphere
d108.dat	background	empty chamber
d109.dat	target	15.24 cm diameter sphere

Three measurement steps were taken for each target: calibration, background, and target. With a 128 averaging factor, 60 seconds were required for a complete sweep of 801 frequency points, 15 seconds to transfer data from the HP-8510B to the PC, and 10 seconds to store this data to the hard disk. When no averaging is taken, sweeping through 801 frequency steps takes 40 seconds, most of it is for phase-locking the receiver. As the averaging factor increases, the



sweep time also increases progressively to the maximum of 700 seconds for the maximum averaging factor of 4096. Trade-offs between the averaging factor and the measurement time must be considered in selecting the averaging factor.

The MIE2.BAS program was executed for the 12.07 cm calibration sphere. The computation includes the small bistatic angle between two antennas and provides the magnitude and phase of  $H_{CC}$ . These data were stored under filenames of "mag.dat" and "faz.dat".

Results of the "PROC.M" post-processing program are shown in Figures 17 through 22. Figures 17, 19, and 21 show the frequency responses of the target spheres, with the measurement data plotted in dotted lines, and theoretical values from the Mie solution in solid lines. Comparison of the frequency responses shows good agreement, and thus confirms the validity of the measurement system. Figures 18, 20, and 21 show the corresponding time responses. The time responses represent the scattered waveform resulting from the incident impulse formed by the inverse transform of the 2-18 GHz bandlimited signal weighted by the Hamming window. The time responses show the main specular return, from the front face of the sphere, followed by the creeping-wave, delayed in time corresponding to a single circumnavigation.

A detailed comparison between the measurement data and computational data in the frequency responses indicates a minor discrepancy of less than 1 dB in magnitude. This

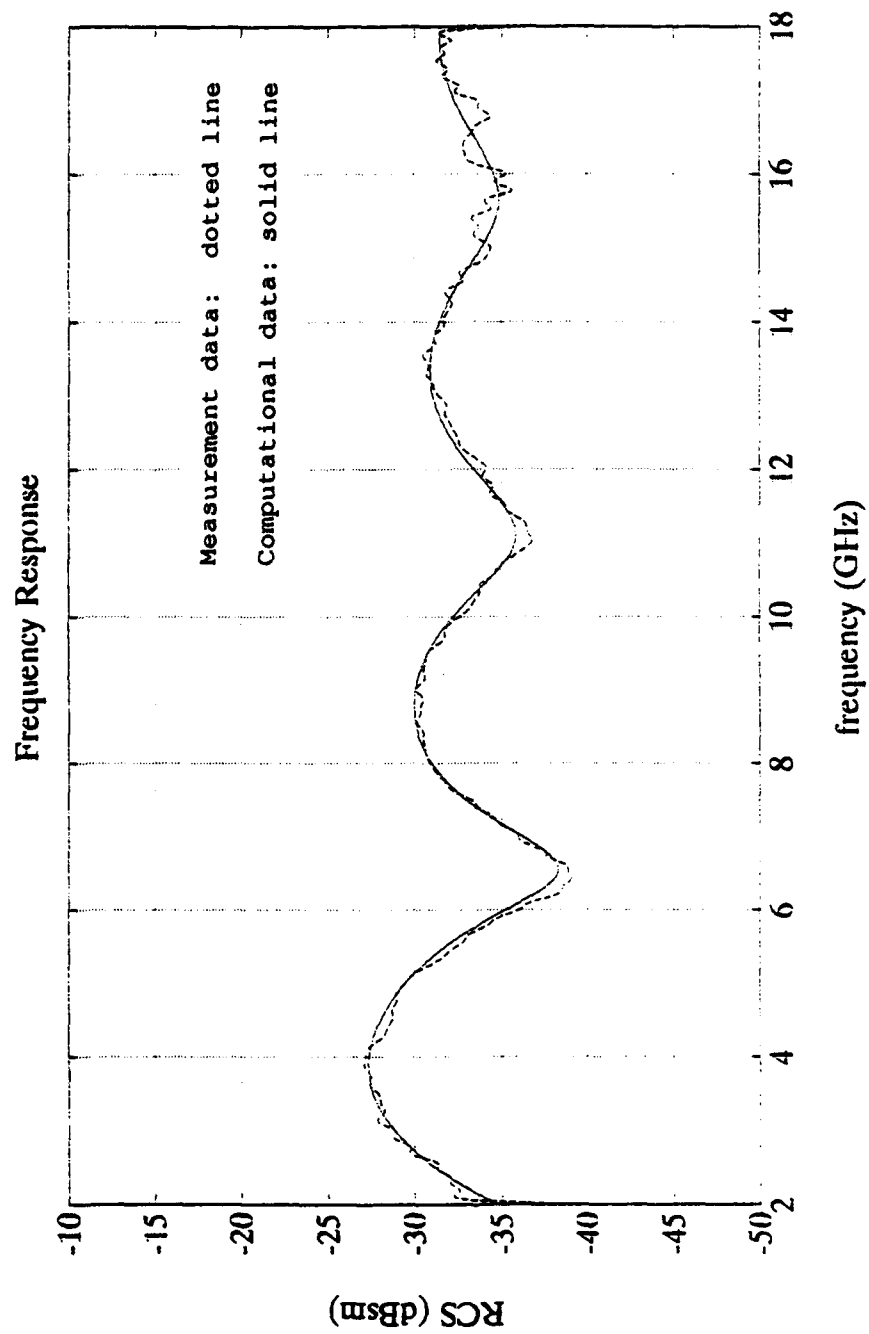


Figure 17. Frequency Response of a 2.54 cm Diameter Sphere

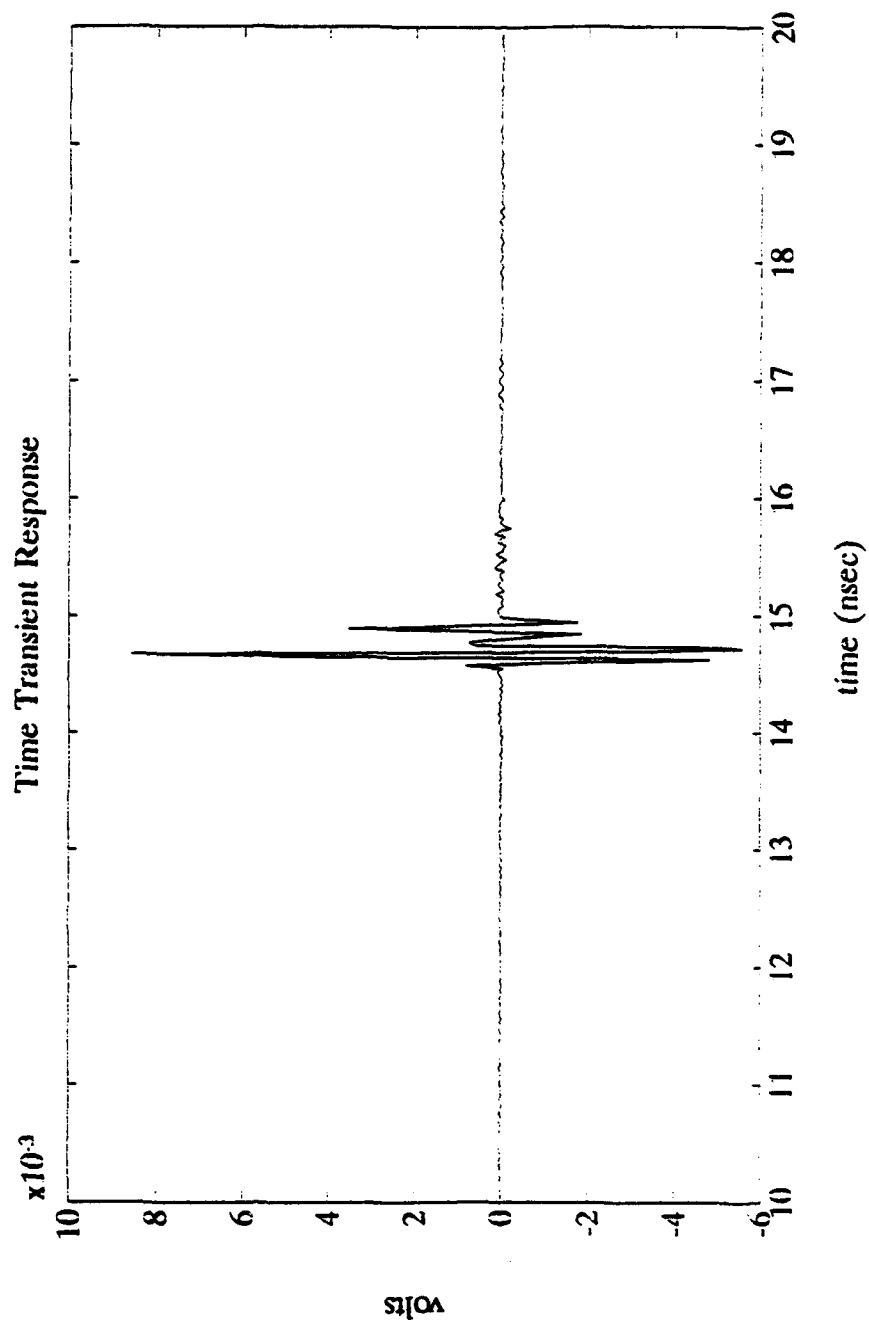


Figure 18. Time Transient Response of a 2.54 cm Diameter Sphere

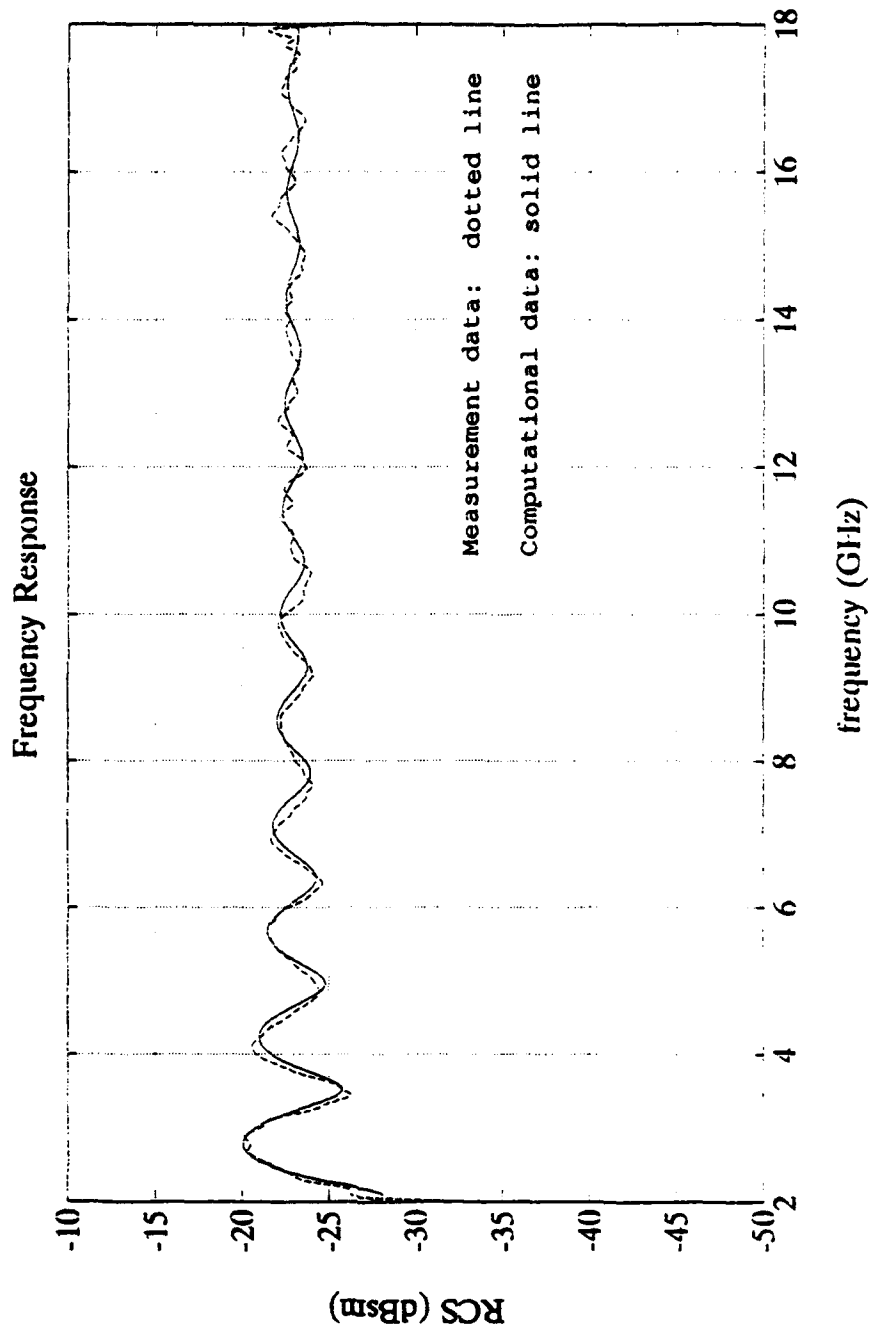


Figure 19. Frequency Response of a 7.94 cm Diameter Sphere

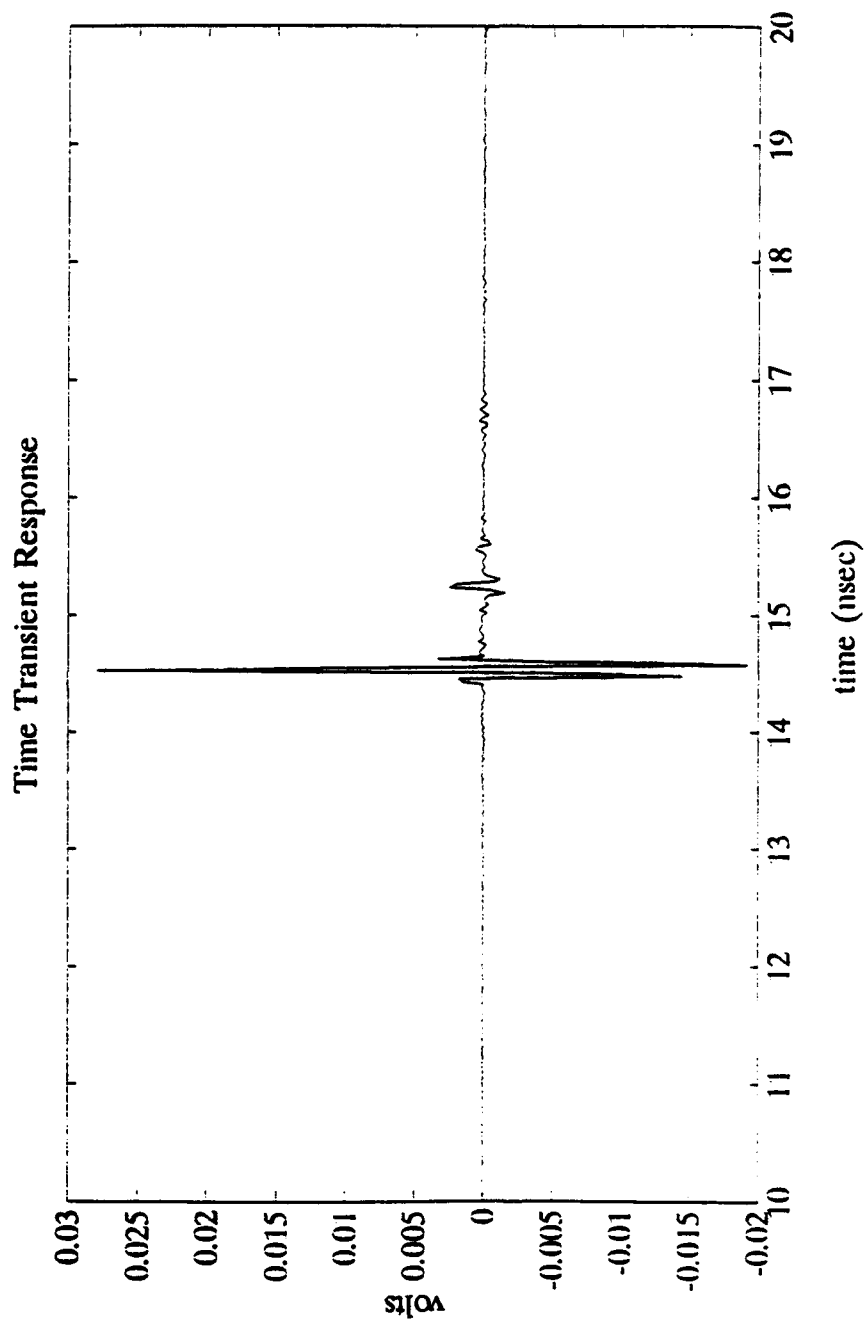


Figure 20. Time Transient Response of a 7.94 cm Diameter Sphere

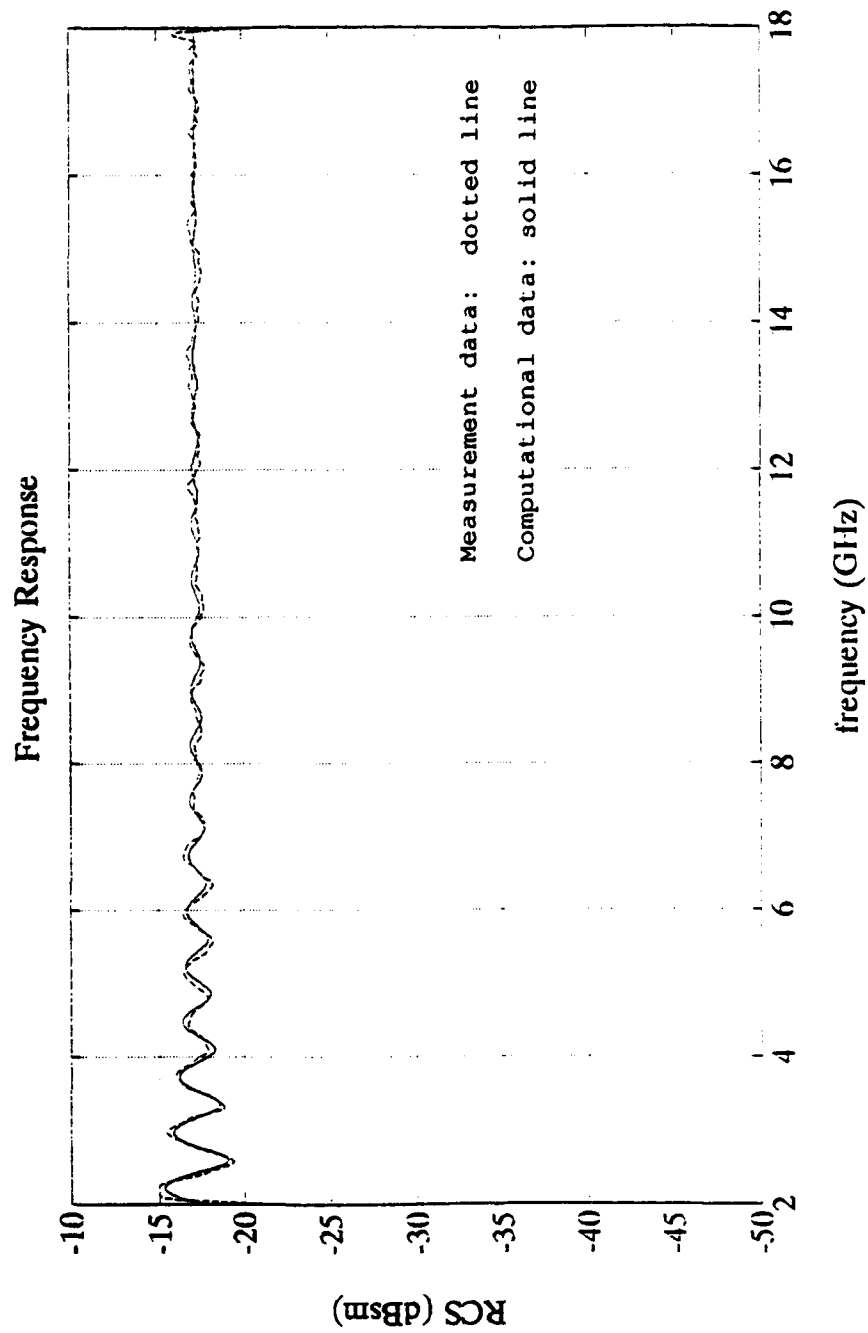


Figure 21. Frequency Response of a 15.24 cm Diameter Sphere

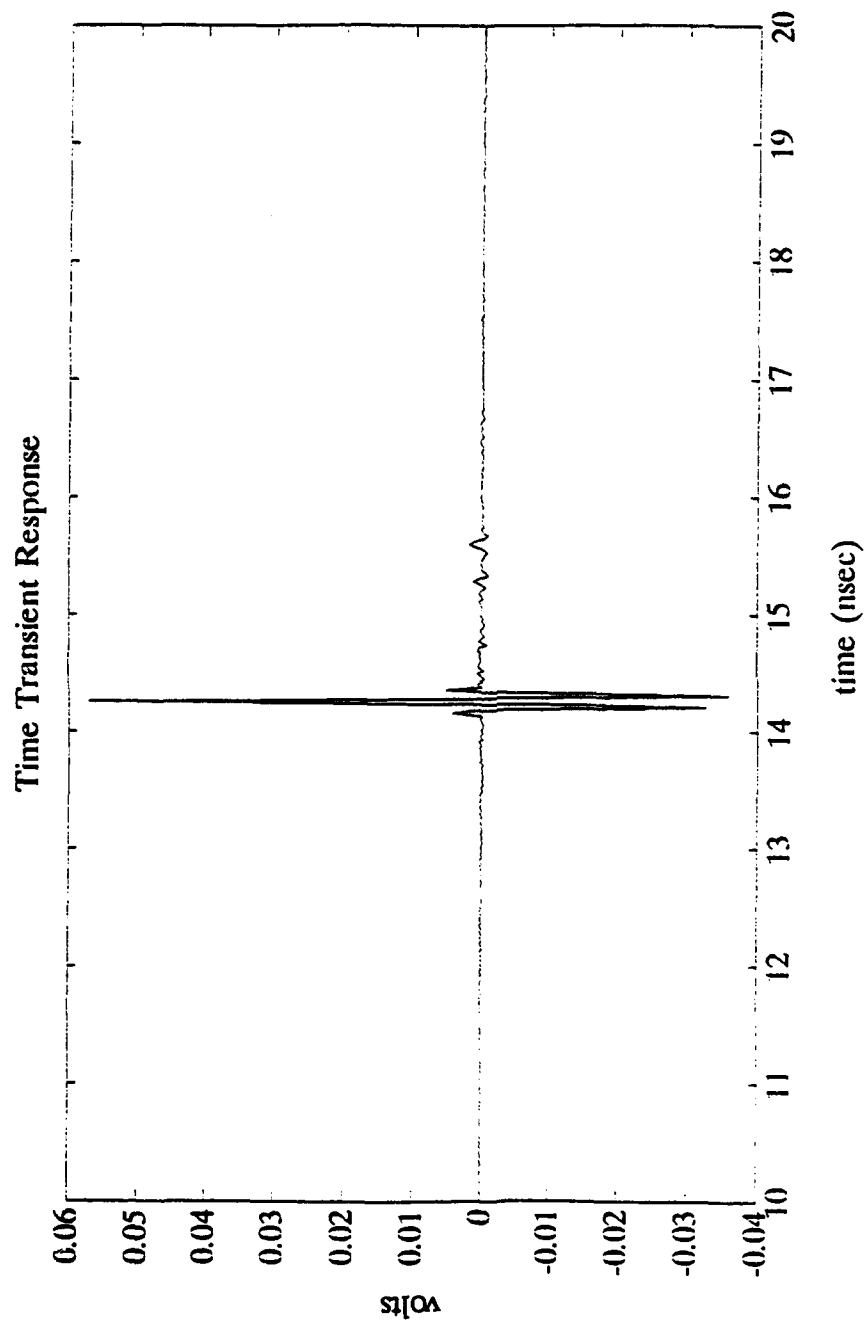


Figure 22. Time Transient Response of a 15.24 cm Diameter Sphere

discrepancy remained even when the averaging factor was increased substantially, showing that the error results from coherent sources. Possible error sources are 1) interaction between the sphere and the chamber, 2) disturbance of fields on the sphere caused by the target support column touching the sphere, 3) non-uniform field distribution in the target zone caused by the antenna beam pattern, and 4) imperfections in the sphere's surface radius, as well as scratches and dents. Despite these possible error sources, the measurement results are in good agreement with the computational data, thus confirming the validity of the measurement system and post-processing algorithm.



## **VI. CONCLUSIONS**

### **A. SUMMARY**

A new frequency-domain electromagnetic scattering measurement capability has been developed for the NPS TESL anechoic chamber. The new system takes advantage of the HP-8510B network analyzer for its broad frequency coverage, wide dynamic range, and automated control of sub-systems. A pair of AEL H1498 horns operating at 2 to 18 GHz is installed as transmitting and receiving antennas. An HP-82300C BASIC Language Processor installed on a COMPAQ Deskpro-386 PC enables remote control of the HP-8510B and data acquisition over the HPIB bus. A post-processing algorithm has been developed in MatLab for background subtraction, calibration, windowing, adding zeros and conjugates, IFFT, shifting, gating, and FFT.

The new system was utilized to measure the scattered fields from several different-size spheres. Good agreement between the measurements and computational Mie series demonstrated the validity of the measurement system and the post-processing algorithm.

### **B. FUTURE CONSIDERATIONS**

The antenna component needs to be improved to enhance the measurement fidelity and expand the frequency bandwidth. For

low frequencies, the increased antenna coupling limits the dynamic range and SNR of the system. The coupling between antennas must be reduced by either moving them apart, inserting RAM between them, finding a new antenna that controls the coupling better, or gating the RF in hardware. The antenna also limits the frequency bandwidth. The frequency coverage of the current system can be increased to 26 GHz by upgrading the antennas and the directional coupler.

When the new improved antennas are implemented to reduce the antenna coupling, the RAMP mode of the HP8510B may be used to speed up the measurement time. In the RAMP mode, the network analyzer sweeps through the 801 frequency points in a fraction of a second.

One of the advantages of the HP-8510B based system is its flexibility for expansion into the millimeter-wave region. With a simple addition of a second RF source, frequency multipliers, and millimeter-wave components such as a directional coupler and antennas, the frequency range of the RCS measurement can be extended to 110 GHz.

One last consideration for the future is incorporating a pedestal for the rotation of targets. The ability to rotate the target in precise angle increments and correcting coherent data at different aspect angles allows the generation of two-dimensional scattering images of the target using inverse synthetic aperture radar (ISAR) techniques.

# APPENDIX A. SOURCE CODE OF THE "GET\_DATA" PROGRAM

```

10 ! GET_DATA: THIS HP BASIC PROGRAM CONTROLS HP8510
20 ! REMOTELY AND WRITES MAG & PHASE DATA ON PC
30 ! HARD DISK UNDER C:\BLPSUBDIRECTORATE.
40 ! WRITTEN BY KEN OH
50 ! REVISED ON 9/2/93
60 OPTION BASE 1
70 COM REAL Exp_tbl(0:255)
80 MASS STORAGE IS "\BLP:DOS,C"
90 PRINTER IS 1
100 PRINT CHR$(12)
110 ASSIGN @Hpib TO 7
120 ASSIGN @Nwa TO 716
130 REMOTE @Hpib
140 CLEAR @Nwa
150 Exp_tbl(0)=2^(-15)
160 FOR I=0 TO 126
170     Exp_tbl(I+1)=Exp_tbl(I)+Exp_tbl(I)
180 NEXT I
190 Exp_tbl(128)=2^(-143)
200 FOR I=128 TO 254
210     Exp_tbl(I+1)=Exp_tbl(I)+Exp_tbl(I)
220 NEXT I
230 Main menu: !
240 PRINT CHR$(12)
250 OUTPUT @Nwa;"STAR;OUTPACTI;"
260 ENTER @Nwa;Star_freq
270 OUTPUT @Nwa;"STOP;OUTPACTI;"
280 ENTER @Nwa;Stop_freq
290 OUTPUT @Nwa;"POIN;OUTPACTI;"
300 ENTER @Nwa;Npoint
310 OUTPUT @Nwa;"POWE;OUTPACTI;"
320 ENTER @Nwa;Power
330 OUTPUT @Nwa;"SWEM?;"
340 ENTER @Nwa;Swe$
350 OUTPUT @Nwa;"CAL$?;"
360 ENTER @Nwa;Calset
370 OUTPUT @Nwa;"AVERON;OUTPACTI;"
380 ENTER @Nwa;Avn
390 OUTPUT @Nwa;"ENTO;"
400 DISP
410 PRINT "Main Menu"
420 PRINT " "
430 PRINT "START FREQ IS: ";Star_freq/1.E+9;"GHz"
440 PRINT "STOP FREQ IS: ";Stop_freq/1.E+9;"GHz"
450 PRINT "NUMBER OF POINTS IS: ";Npoint

```

```

460 PRINT "SOURCE POWER IS: ";INT(Power+.001); "dBm"
470 PRINT "SWEEP MODE IS: ";Swe$
480 PRINT "ACTIVE CAL SET IS: ";Calset
490 PRINT "AVERAGING FACTOR IS: ";Avn
500 OFF KEY
510 ON KEY 1 LABEL "Continu.Sweep" GOTO Cont_sweep
520 ON KEY 2 LABEL "Single Sweep" GOTO Sing_sweep
530 ON KEY 3 LABEL "Hold Sweep" GOTO Hold_sweep
540 ON KEY 4 LABEL "Change #Average" GOTO Average
550 ON KEY 5 LABEL "Record Data" GOTO Call_record
560 ON KEY 6 LABEL "PlaybackData" GOTO Call_playback
570 ON KEY 7 LABEL "Change Setup" GOTO Setup
580 ON KEY 8 LABEL "Default Setup" GOTO Default
590 GOTO 510
600 !
610 !
620 Cont_sweep: !
630 DISP "CONTINUOUS SWEEP"
640 OUTPUT @Nwa;"CONT;";
650 GOTO Main_menu
660 Sing_sweep: !
670 DISP "SINGLE SWEEP .... PLEASE WAIT"
680 OUTPUT @Nwa;"SING;";
690 GOTO Main_menu
700 Hold_sweep: !
710 DISP "HOLD SWEEP"
720 OUTPUT @Nwa;"HOLD;";
730 GOTO Main_menu
740 Average: !
750 INPUT "ENTER THE NUMBER OF AVERAGE: ",Avn
760 OUTPUT @Nwa;"AVERON";Avn
770 GOTO Main_menu
780 Call_record: !
790 DISP "RECORDING DATA.... PLEASE WAIT."
800 CALL Record_data(Npoint)
810 GOTO Main_menu
820 Call_playback: !
830 DISP "READING DATA.... PLEASE WAIT."
840 CALL Playback_data(Npoint)
850 GOTO Main_menu
860 Setup: !
870 PRINT CHR$(12)
880 OUTPUT @Nwa;"STAR;OUTPACTI;";
890 ENTER @Nwa;Star_freq
900 OUTPUT @Nwa;"STOP;OUTPACTI;";
910 ENTER @Nwa;Stop_freq
920 OUTPUT @Nwa;"POIN;OUTPACTI;";
930 ENTER @Nwa;Npoint
940 OUTPUT @Nwa;"POWE;OUTPACTI;";
950 ENTER @Nwa;Power
960 OUTPUT @Nwa;"SWEM?;";

```

```

970  ENTER @Nwa;Swe$
980  OUTPUT @Nwa;"CAL$?;"
990  ENTER @Nwa;Calset
1000 PRINT "Setup Menu"
1010 PRINT " "
1020 PRINT "START FREQ IS: ";Star_freq/1.E+9;"GHz"
1030 PRINT "STOP FREQ IS: ";Stop_freq/1.E+9;"GHz"
1040 PRINT "NUMBER OF POINTS IS: ";Npoint
1050 PRINT "SOURCE POWER IS: ";INT(Power+.001);"dBm"
1060 PRINT "SWEEP MODE IS: ";Swe$
1070 PRINT "ACTIVE CAL SET IS: ";Calset
1080 OFF KEY
1090 ON KEY 1 LABEL "Save State" GOTO Save_state
1100 ON KEY 2 LABEL "Recall State" GOTO Recall_state
1110 ON KEY 3 LABEL "Change Freq" GOTO Freq_range
1120 ON KEY 4 LABEL "No of Point" GOTO No_point
1130 ON KEY 5 LABEL "Power Level" GOTO Power
1140 ON KEY 6 LABEL "Sweep Mode" GOTO Sweep_mode
1150 ON KEY 7 LABEL "Calibra-tion" GOTO Call_cal
1160 ON KEY 8 LABEL "Go to MainMenu" GOTO Main_menu
1170 GOTO 1090
1180 Recall_state:
1190 INPUT "ENTER RECALL STATE NUMBER: ",Sset
1200 OUTPUT @Nwa;"RECA"&VAL$(Sset)
1210 GOTO Setup
1220 Save_state:
1230 INPUT "ENTER SAVE STATE NUMBER: ",Sset
1240 OUTPUT @Nwa;"SAVE"&VAL$(Sset)
1250 GOTO Setup
1260 Freq_range:
1270 INPUT "ENTER START FREQ IN GHz: ",Star_freq
1280 INPUT "ENTER STOP FREQ IN GHz: ",Stop_freq
1290 OUTPUT @Nwa;"STAR";Star_freq;"GHz;"
1300 OUTPUT @Nwa;"STOP";Stop_freq;"GHz;"
1310 GOTO Setup
1320 No_point:
1330 INPUT "ENTER NUMBER OF POINT (51,101,201,401 or 801): ",Npoint
1340 OUTPUT @Nwa;"POIN",Npoint
1350 GOTO Setup
1360 Power:
1370 INPUT "ENTER SOURCE POWER LEVEL IN dBm: ",Power
1380 OUTPUT @Nwa;"POWE",Power
1390 GOTO Setup
1400 Sweep_mode:
1410 INPUT "ENTER 1 FOR STEP MODE AND 2 FOR RAMP MODE: ",Sweep
1420 IF Sweep=2 THEN
1430 GOTO Ramp_mode
1440 ELSE
1450 GOTO Step_mode

```

```

1460 END IF
1470 Step_mode: !
1480 OUTPUT @Nwa;"STEP;"
1490 GOTO Setup
1500 Ramp_mode: !
1510 OUTPUT @Nwa;"RAMP;"
1520 GOTO Setup
1530 Call_cal: !
1540 INPUT "ENTER CAL SET NO (1-8), OR 0 FOR NEW CAL, OR 9
FOR CAL OFF",Cn
1550 IF Cn=0 THEN
1560     CALL Calibrate(Npoint)
1570     GOTO Main1
1580 END IF
1590 IF Cn<9 THEN
1600     OUTPUT @Nwa;"CORRON;"
1610     OUTPUT @Nwa;"CALS"&VAL$(Cn)
1620 ELSE
1630     OUTPUT @Nwa;"CORROFF;"
1640 END IF
1650 GOTO Setup
1660 Default: !
1670 DISP "PRESETTING THE NWA ... PLEASE WAIT."
1680 OUTPUT @Nwa;"PRES;"
1690 OUTPUT @Nwa;"STAR 2 GHz;STOP 18 GHz;"
1700 OUTPUT @Nwa;"POIN801;"
1710 OUTPUT @Nwa;"STEP;"
1720 OUTPUT @Nwa;"CONT;"
1730 OUTPUT @Nwa;"OUTPERRO;"
1740 GOTO Main_menu
1750 !!
1760 STOP
1770 END
1780 !!
1790 SUB Calibrate(Npoint)
1800     OPTION BASE 1
1810     ASSIGN @Nwa TO 716
1820     ASSIGN @Nwa_data2 TO 716;FORMAT OFF
1830     INTEGER Preamble,Size,Cals
1840     DIM Room(801,2),Reference(801,2),Source(801,2)
1850     DISP CHR$(129)&"MEASURE ROOM,"&CHR$(128)&" THEN PRES
S CONTINUE"
1860     BEEP
1870     LOCAL 716
1880     PAUSE
1890     OUTPUT @Nwa;"FORM3;OUTPRAW1"
1900     ENTER @Nwa_data2;Preamble,Size,Room(*)
1910     !
1920     DISP CHR$(129)&"MEASURE REFERENCE,"&CHR$(128)&" THEN
PRESS CONTINUE"
1930     BEEP

```

```

1940     LOCAL 716
1950     PAUSE
1960     OUTPUT @Nwa;"FORM3;OUTPRAW1"
1970     ENTER @Nwa_data2;Preamble,Size,Reference(*)
1980     !
1990     DISP CHR$(131)&"SUBTRACTING OUT"&CHR$(128)&" THE EFF
ECTS OF THE ROOM"
2000     FOR M=1 TO 2
2010         FOR N=1 TO Npoint
2020             Reference(N,M)=Reference(N,M)-Room(N,M)
2030         NEXT N
2040     NEXT M
2050     !
2060     INPUT "ENTER CAL SET NUMBER (1-8) AND PRESS CONTINUE
",Cals
2070     BEEP
2080     IF Cals=0 THEN GOTO 2060
2090     DISP CHR$(131)&"LOADING"&CHR$(128)&" CAL COEFFICIEN
TS"
2100     OUTPUT @Nwa;"CAL1;CALIS111"
2110     OUTPUT @Nwa;"FORM3;INPUCALC01"
2120     OUTPUT @Nwa_data2;Preamble,Size,Room(*)
2130     OUTPUT @Nwa;"FORM3;INPUCALC02"
2140     OUTPUT @Nwa_data2;Preamble,Size,Source(*)
2150     OUTPUT @Nwa;"FORM3;INPUCALC03"
2160     OUTPUT @Nwa_data2;Preamble,Size,Reference(*)
2170     OUTPUT @Nwa;"SAVC;CALS"&VAL$(Cals)
2180     DISP
2190     LOCAL 716
2200     SUBEND
2210     !!
2220     SUB Record_data(Npoint)
2230         OPTION BASE 1
2240         ASSIGN @HpiB TO 7
2250         ASSIGN @Nwa TO 716
2260         PRINTER IS 1
2270         REAL Freq(1:801),Mag(1:801),Phase(1:801)
2280         REAL Block(1:801,1:2)
2290         INTEGER Binary(1:801,0:2)
2300         INTEGER I,Points,M,N
2310         COM Exp_tbl(*)
2320         REMOTE @HpiB
2330         ABORT @HpiB
2340         CLEAR @Nwa
2350         Points=Npoint
2360         Enter_data(@Nwa,Points,Binary(*))
2370         Convertb(Points,Binary(*),Block(*))
2380         Transform(Points,Block(*),Mag(*),Phase(*))
2390         CLEAR @Nwa
2400         BEEP
2410         PRINT CHR$(12)

```

```

2420 DISP
2430 GINIT !*****PLOT GRAPH
2440 GCLEAR
2450 GRAPHICS ON
2460 VIEWPORT 10,140,60,100
2470 FRAME
2480 Maxv=-10000
2490 N=Npoint
2500 FOR I=1 TO N
2510 Maxv=MAX(Maxv,Mag(I))
2520 NEXT I
2530 WINDOW 1,N,Maxv-40,Maxv+5
2540 FOR I=1 TO N
2550 MOVE I,-200
2560 DRAW I,Mag(I)
2570 NEXT I
2580 VIEWPORT 10,140,10,50
2590 FRAME
2600 WINDOW 1,N,-180,180
2610 FOR I=1 TO N
2620 MOVE I,0
2630 DRAW I,Phase(I)
2640 NEXT I
2650 !
2660 PAUSE
2670 GCLEAR
2680 !
2690 !FILE CREATOR
2700 INPUT "ENTER NEW FILE NUMBER =",Istrt
2710 Filen$=""
2720 DISP "WRITING DATA TO DISK.... PLEASE WAIT"
2730 Filen$="F"&VAL$(Istrt)&".DAT"
2740 CREATE BDAT Filen$,26,256
2750 ASSIGN @Path TO Filen$
2760 OUTPUT @Path;Mag(*),Phase(*)
2770 ASSIGN @Path TO *
2780 Filen$="D"&VAL$(Istrt)&".DAT"
2790 CREATE Filen$,256
2800 ASSIGN @Path2 TO Filen$
2810 FOR I=1 TO N
2820 OUTPUT @Path2 USING "K";I,CHR$(44),Mag(I),CHR$(44)
,Phase(I)
2830 NEXT I
2840 GCLEAR
2850 ASSIGN @Path2 TO *
2860 SUBEND
2870 !!
2880 DEF FNAtan(X,Y,P)
2890 IF X=0 THEN X=.E-9
2900 D=ATN(Y/X)
2910 IF (X<0) AND (Y>0) THEN P=D+PI

```



```

2920     IF (X<0) AND (Y<0) THEN P=D-PI
2930     IF X>0 THEN P=D
2940     RETURN P
2950 FNEND
2960 !!
2970 SUB Print_data(INTEGER N,REAL X(*),REAL Y(*),REAL M(*)
)
2980     INTEGER I
2990     FOR I=1 TO 128
3000         PRINT USING "4(5D.DD)";I,X(I),Y(I),M(I)
3010     NEXT I
3020 SUBEND
3030 !!
3040 SUB Enter_data(@N,INTEGER N,D(*))
3050     INTEGER Preamble,Bytes
3060     OUTPUT @N;"FORM1; OUTPDATA;"
3070     ASSIGN @N;FORMAT OFF
3080     ENTER @N;Preamble;Bytes
3090     N=Bytes/6
3100     REDIM D(1:N,0:2)
3110     ENTER @N;D(*)
3120     ASSIGN @N;FORMAT ON
3130 SUBEND
3140 !!
3150 SUB Transform(INTEGER N,REAL D(*),M(*),P(*))
3160     INTEGER I
3170     REAL R,Im,Mag
3180     DEG
3190     FOR I=1 TO N
3200         R=D(I,1)
3210         Im=D(I,2)
3220         Mag=SQR(R*R+Im*Im)
3230         M(I)=20*LGT(Mag)
3240         P(I)=2*ATN(Im/(R+Mag))
3250     NEXT I
3260 SUBEND
3270 !!
3280 SUB Convertb(INTEGER N,B(*),REAL D(*))
3290     INTEGER I
3300     REAL Exp
3310     COM Exp_tbl(*)
3320     FOR I=1 TO N
3330         Exp=Exp_tbl(BINAND(B(I,2),255))
3340         D(I,1)=B(I,1)*Exp
3350         D(I,2)=B(I,0)*Exp
3360     NEXT I
3370 SUBEND
3380 !!
3390 DEF FNLgt(X,Y)
3400     Z=X^2+Y^2
3410     IF Z>.000001 THEN

```

```

3420     Vlog=10*LGT(Z)
3430     ELSE
3440     Vlog=-200
3450     END IF
3460     RETURN Vlog
3470 FNEND
3480 !!
3490 SUB Playback_data(Npoint)
3500     OPTION BASE 1
3510     ASSIGN @Hpib TO 7
3520     ASSIGN @Nwa TO 716
3530     PRINTER IS 1
3540     REAL Freq(1:801),Mag(1:801),Phase(1:801)
3550     REAL Block(1:801,1:2)
3560     INTEGER Binary(1:801,0:2)
3570     INTEGER I,Points,M,N
3580     COM Exp tbl(*)
3590     INPUT "ENTER FILE NUMBER =",Num
3600     Fname$="F"&VAL$(Num)
3610     OUTPUT KBD;Clear$;
3620     OUTPUT KBD;Home$;
3630     ASSIGN @Path TO Fname$
3640     ENTER @Path;Mag(*),Phase(*)
3650     PRINT CHR$(12)
3660     DISP
3670     GINIT          !*****PLOT GRAPH
3680     GCLEAR
3690     GRAPHICS ON
3700     VIEWPORT 10,140,60,100
3710     FRAME
3720     Maxv=-10000
3730     N=Npoint
3740     FOR I=1 TO N
3750         Maxv=MAX(Maxv,Mag(I))
3760     NEXT I
3770     WINDOW 1,N,Maxv-40,Maxv+5
3780     FOR I=1 TO N
3790         MOVE I,-200
3800         DRAW I,Mag(I)
3810     NEXT I
3820     VIEWPORT 10,140,10,50
3830     FRAME
3840     WINDOW 1,N,-180,180
3850     FOR I=1 TO N
3860         MOVE I,0
3870         DRAW I,Phase(I)
3880     NEXT I
3890     PAUSE
3900     GCLEAR
3910 SUBEND

```

## APPENDIX B. SOURCE CODE OF THE "PROC.M" PROGRAM

```

% Post-processing program
% REV. 6/24/93   Ken Oh

clear, clg

filename=input('Enter Cal File:      d101 ','s');
eval(['load ',filename,'.dat'])
data1=eval(filename);

filename=input('Enter BG File:      d102 ','s');
eval(['load ',filename,'.dat'])
data2=eval(filename);

filename=input('Enter Target File: d103 ','s');
eval(['load ',filename,'.dat'])
data3=eval(filename);

filename=input('Enter Computed Sphere Mag File:  mag ','s');
eval(['load ',filename,'.dat'])
data4=eval(filename);

filename=input('Enter Computed Sphere Phase File:faz ','s');
eval(['load ',filename,'.dat'])
data5=eval(filename);

filename=input('Enter Target Mie File: m1, m2, or m3 ','s');
eval(['load ',filename,'.dat'])
data6=eval(filename);

j=sqrt(-1);,   npoint=801;
freq=[2:(18-2)/800:18]';
t=[0:50/800:50]';
t2048=[0:50/2047:50]';
tzoom=[10:10/409:20]';

% ***** Calibration Data
m1=zeros(1,npoint);
p1=zeros(1,npoint);
for i=1:npoint
    m1(i)=data1(i,2);           % in db
    p1(i)=data1(i,3);           % in degree
end;
m1=10.^(m1/20);                % in linear unit
p1=p1*pi/180;                  % in radian
d1=m1.*cos(p1)+j*m1.*sin(p1);

```

```

% ***** Background Data
m2=zeros(1,npoint);
p2=zeros(1,npoint);
for i=1:npoint
    m2(i)=data2(i,2);           % in db
    p2(i)=data2(i,3);           % in degree
end;
m2=10.^(m2/20);                 % in linear unit
p2=p2*pi/180;                   % in radian
d2=m2.*cos(p2)+j*m2.*sin(p2);

% ***** Target Data
m3=zeros(1,npoint);
p3=zeros(1,npoint);
for i=1:npoint
    m3(i)=data3(i,2);           % in db
    p3(i)=data3(i,3);           % in degree
end;
m3=10.^(m3/20);                 % in linear unit
p3=p3*pi/180;                   % in radian
d3=m3.*cos(p3)+j*m3.*sin(p3);

% ***** Computed Sphere Data
m4=zeros(1,npoint);
p4=zeros(1,npoint);
for i=1:npoint
    m4(i)=data4(i+4);
    p4(i)=data5(i+4);
end;
d4=m4.*cos(p4)+j*m4.*sin(p4);

% ***** Target's Mie Solution
m6=zeros(1,npoint);
for i=1:npoint
    m6(i)=data6(i+4);
end;

clf
plot(freq,m3)
title('Target Raw Data')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
%printlj
pause

% *****
d12=d1-d2;                       % Subtracting BG from Cal
d32=d3-d2;                       % Subtracting BG from Target

clf
plot(freq,abs(d32))

```

```

title('Frequency Response after Background Subtraction')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
%printlj
pause

% ***** Calibration
f32c=d32./d12.*d4;

clg
plot(freq,abs(f32c))
title('Frequency Response after Calibration')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
%printlj
pause

% ***** Hamming window
win=hamming(npoint);
f32cw=f32c.*win';

clg
plot(freq,win)
title('Hamming Window')
xlabel('frequency (GHz)'), ylabel('weighting factor')
%printlj
pause
clg
plot(freq,abs(f32cw))
title('Frequency Response after Windowing')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
%printlj
pause

% ***** Adding zeros and conjugates
ff=zeros(1:2048);
ff([101:901])=f32cw;
ff([1149:1949])=conj(f32cw(801:-1:1));

clg
plot(abs(ff))
title('Frequency Response after Adding zeros and Conjugates')
)
xlabel('index number'), ylabel('magnitude (volts)')
%printlj
pause

tt=ifft(ff); % Inverse FFT to time domain
clg
plot(t2048,real(tt))
title('Time Response before Shifting')
xlabel('time (nsec)'), ylabel('magnitude (volts)')

```

```

%printlj
pause

temp=zeros(1:1459);
temp=tt([1:1459]);
tt([1:589])=tt([1460:2048]);
    % Shifting data to put cross-talk at time zero.
tt([590:2048])=temp;
clg
plot(t2048,real(tt))
title('Time Response after Shifting')
xlabel('time (nsec)'), ylabel('magnitude (volts)')
%printlj
pause

g1=zeros(1:400);
g2=zeros(1:1248);
tt([1:400])=g1;
tt([801:2048])=g2;
    % Gate width = 400 cells
clg
plot(t2048,real(tt))
title('Time Response after Gating')
xlabel('time (nsec)'), ylabel('magnitude (volts)')
%printlj
pause
clg
plot(tzoom,real(tt([411:820])));
title('Zoom-in View of Time Response')
xlabel('time (nsec)'), ylabel('magnitude (volts)')
%printlj
pause

ffg=fft(tt);
    % FFT to frequency response
clg
plot(abs(ffg))
title('Frequency Response Showing All 2048 points')
xlabel('index number'), ylabel('magnitude (volts)')
%printlj
pause

f32cg=zeros(1:801);
f32cg=ffg([101:901]);
    % throw-away zeros and conjugates
clg
plot(freq,abs(f32cg))
title('Frequency Response from 2 GHz to 18 GHz')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
%printlj
pause

win_inv=1./win';
f32cg=f32cg.*win_inv;

```

```

clg
plot(freq,win_inv)
title('Inverse of Hamming Window')
xlabel('frequency (GHz)'), ylabel('weighting factor')
fprintf
pause

clg
plot(freq,abs(f32cg))
title('Frequency Response after Unwindowing')
xlabel('frequency (GHz)'), ylabel('magnitude (volts)')
fprintf
pause

clg
axis([2 18 -50 -10])
plot(freq,20*log10(abs(f32cg)),'--',freq,20*log10(m6),'-')
title('Frequency Response')
xlabel('frequency (GHz)'), ylabel('RCS (dBsm)')
grid
fprintf
axis;

end;

```

### LIST OF REFERENCES

1. "Operating and Programming Manual: HP-8510B Network Analyzer", Hewlett Packard, April 1988.
2. M.A. Mariatequi, "Development, Calibration, and Evaluation of a Free Field Scattering Range", Master's Thesis, Naval Postgraduate School, Monterey, CA, 1983.
3. Brent W. McDaniel, "Calibration and Evaluation of a Free Field Scattering Range Using Wideband Pulse Amplification", Master's Thesis, Naval Postgraduate School, Monterey, CA, 1985.
4. "Antenna, Antenna Masts, Mounts and Adapters", American Electronic Laboratories (AEL) Inc., 1989.
5. "Installing and Using HP-BASIC in the MS-DOS Environment", Order Number 82301-90013, Hewlett Packard, June 1989.
6. "386-MATLAB, Ver. 3.5h", MathWorks Inc., Jan. 1991.



### INITIAL DISTRIBUTION LIST

- |    |  |   |
|----|--|---|
| 1. | Defense Technical Information Center<br>Cameron Station<br>Alexandria, VA 22304-6145   | 2 |
| 2. | Library, Code 52<br>Naval Postgraduate School<br>Monterey, CA 93943-5101   | 2 |
| 3. | Department Chairman, Code EC<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, CA 93943-5121            | 1 |
| 4. | Professor Michael A. Morgan, Code EC/Mw<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, CA 93943-5100 | 4 |
| 5. | Professor David C. Jenn, Code EC/Jn<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, CA 93943-5100     | 1 |
| 6. | Professor Rama Janaswamy, Code EC/Js<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, CA 93943-5100    | 1 |
| 7. | Dr. Dean Mensa, Code P03923<br>Naval Air Warfare Center-Weapons Division<br>Point Mugu, CA 93042-5000  | 2 |
| 8. | Dr. Peter Yu, Code P03923<br>Naval Air Warfare Center-Weapons Division<br>Point Mugu, CA 93042-5000  | 1 |
| 9. | Technical Library, Code P6433A<br>BLDG 511A<br>Naval Air Warfare Center-Weapons Division<br>Point Mugu, CA 93042-5000                                | 1 |